Training Module

On

Constructed Wetlands: Principles, Design, Operation, and Maintenance

सत्यमेव जयते
Department of Science & Technology
Govt. of India

Organized by

National Institute of Hydrology
Jal Vigyan Bhawan
Roorkee

Sponsored by

Dept. of Science & Technology
Govt. of India
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Project Partners

Preface

Water management and environmental sustainability are crucial issues in our rapidly developing world. To balance growth with protecting our environment, innovative solutions for managing wastewater are essential. Constructed wetlands are natural and effective way to treat wastewater, using natural processes to tackle environmental challenges.

This module is based on the training course entitled "Constructed Wetlands: Principles, Design, Operation, and Maintenance," organized by the Environmental Hydrology Division of National Institute of Hydrology (NIH), Roorkee during July 1-5, 2024, sponsored by the Department of Science & Technology, GoI under the project IC-EcoWS. The training course is primarily designed for professionals in wastewater management but also serves as a valuable resource for students and researchers who want to contribute to this important field. The subject experts have been selected to provide their inputs in the form of lectures from IC-EcoWS project partners and industries. It brought together top scientists, engineers, researchers, and policymakers to explore the utility of constructed wetlands under different setups in urban and rural areas.

The chapters provide a thorough overview of how constructed wetlands work along with practical case studies. The module explains how these systems use plants, soil, and microorganisms to treat different types of wastewater. It also discusses the design and maintenance of these systems, highlighting important factors like water flow, substrate composition, plant selection, and contaminant management. Throughout the module, readers will learn about advanced topics such as the cost-effectiveness of natural wastewater treatment systems, the use of constructed wetlands in various geographical areas, and the integration of energy-efficient treatment technologies.

I am sure that the training course will be of great help to the participants. The organizers of the training course have made their sincere efforts to utilize the best resource persons available for the purpose. The lectures provided by various experts have been compiled by Dr. Rajesh Singh, Scientist 'E'; Dr. Vinay Kumar Tyagi, Scientist 'D'; and Dr. Kalzang Chhoden, Scientist 'C'. I sincerely believe that this compilation would be of great significance and useful for wastewater treatment using natural treatment systems in our country.

28/06/24
(M. K. Goel)
Director, NIH

TRAINING SCHEDULE

Date	Time (HR)	Topic	Faculty
Day-1 July 01, 2024 Monday	09:00 – 10:00	**Registration**	
	10:00 – 10:30	**Inaugural Function**	
	10:30 - 11:00	**Tea**	
	11:00 - 12:15	Constructed Wetland for Wastewater Treatment: An Introduction	RS
	12:15 - 13:30	Wetlands: Role in Water Management	KC
	13:30 - 14:30	**Lunch**	
	14:30 - 15:45	Treatment Mechanism in Constructed Wetlands	ABG
	15:45 – 16:15	**Tea**	
	16:15 – 17:30	Customizing the design of CWs based on treatment standards	ABG
Day-2 July 02, 2024 Tuesday	10:00 - 11:15	Energy Efficient Wastewater Treatment Systems	VKT
	11:15 - 11:45	**Tea**	
	11:45 - 13:00	Constructed Wetlands for Rejuvenation of Village Ponds	OS
	13:00 - 14:00	**Lunch**	
	14:00 - 15:15	Water Quality & Nuclear Hydrology Laboratory Visit	VKT/KC/JS/PKS
	15:15 – 15:45	**Tea**	
	15:45 – 17:00	Economics and Environmental Benefits of Natural Wastewater Treatment Systems	PPK
Day-3 July 03, 2024 Wednesday	10:00 - 11:15	Water Resources Management in India: Challenges & Perspectives	MKG
	11:15 - 11:45	**Tea**	
	11:45 - 13:00	Technology Selection for Eco-Prudent Solutions using JalVishwa	PPK
	13:00 - 14:00	**Lunch**	
	14:00 - 15:15	Aerated Constructed Wetlands: Installations and O&M Issues	GR
	15:15 – 15:45	**Tea**	
	15:45 – 17:00	Constructed Wetlands: Experience In Hilly Regions	DKP
Day-4 July 04, 2024 Thursday	09:00 – 17:30	Field Visit to Demonstrate Constructed Wetlands and Sequencing Batch Reactor Based Wastewater Treatment Systems	RS/VKT/KC/JS
Day-5 July 05, 2024 Friday	09:30 - 10:30	High Performance Advance Septic Systems for Rural Areas: Design, maintenance, and Performance	YRS
	10:30 – 11:30	Cost and Benefits of Constructed Wetlands	ID
	11:30 - 12:00	**Tea**	
	12:00 - 13:00	Regulations and Policies for Implementing Constructed Wetlands	ID
	13:00 - 14:00	**Lunch**	
	14:00 - 15:00	Mainstreaming of CW for wastewater treatment applications in India	VCG
	15:00 – 16:00	Evaluation of Participants and Interaction with Faculties	RS/VKT/KC
	16:00 – 16:30	**Valedictory Function**	
	16:30 – 17:00	**Valedictory Tea**	

Resource Persons:

MKG	:	Dr. M. K. Goel, Director, NIH	KC	:	Dr. Kalzang Chhoden, Scientist 'C', NIH
RS	:	Dr. Rajesh Singh, Scientist 'E', NIH	ABG	:	Prof. A. B. Gupta, MNIT Jaipur
PPK	:	Prof. Pradip P. Kalbar, IIT Bombay, Mumbai	YRS	:	Dr. YRS Rao, Scientist 'G', NIH
VKT	:	Dr. Vinay Kumar Tyagi, Scientist 'D', NIH	JS	:	Dr. Jyoti Singh, RA, NIH
GR	:	Er. Gangadhar Reddy, Blue Drop Enviro, Hyderabad	DP	:	Dr. Dinesh K. Poswal, Rebound Envirotech, Dharamshala
OS	:	Er. Omkar Singh, Scientist 'G', NIH	ID	:	Prof. Indranil De, IRMA, Anand
VCG	:	Dr. V. C. Goyal, Ex. Scientist, NIH	PKS	:	Dr. Prashanta Kumar Sahoo, Scientist 'D', NIH

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Constructed Wetland for Wastewater Treatment: An Introduction

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Globally, ~380 billion m^3 of wastewater is generated annually and only 24% of the household wastewater undergoes some kind of treatment on average[1]. The target-6.3 of United Nations (UN) Sustainable Development Goal-6 (SDG-6) emphasizes improving the quality of water by reducing pollution and reducing the untreated wastewater proportion to half together with recycling and safe reuse[64]. With the increase in population, the wastewater generation volume will increase by 24% in 2030 [2]. There are several conventional and advanced treatment technologies for wastewater treatment across the globe such as activated sludge process (ASP), sequencing bio-reactors (SBR), moving-bed biofilm reactor (MBBR), trickling filters, and Membrane technology. However, these mechanized treatment systems (MTS) need skilled manpower, high energy, and high operation and maintenance costs, which makes them relatively unsustainable for long-term application[3]. Many of these technologies have not considered the sustainable development goal (6.3) by releasing eco-hazardous waste including chemicals in the environment, unsafe waste disposal, and reuse and recycling at high cost in terms of energy[4]. Natural treatment systems (NTS) such as Constructed Wetlands (CW) appear to be an alternative solution to wastewater treatment in place of MTS both economically and environmentally.

Constructed Wetlands (CW) are artificially engineered wetlands consisting of shallow basins (<1m), vegetation (i.e., aquatic macrophytes), microorganisms (e.g., bacteria, protozoa, algae, fungi, yeast), and they may or may not have the substrate (e.g., sand or gravel) depending on the type of CW[5,6]. CW mimics the natural wetlands processes (physical, biological, and chemical) in a more controlled manner [7]. Since 1950, CW has been widely used to treat a variety of wastewater (industrial, agricultural, stormwater, and municipal wastewater), worldwide (Brix, 1994; Ghermandi et al., 2007; Díaz et al., 2012; Guittonny-Philippe et al., 2014; Gholipour et al., 2020; Ventura et al., 2019; Wei et al., 2020; Vymazal et al., 2021; Yadav et al., 2023). They are less complex than the conventional treatment system and have high pollutant removal efficiency for longer operational periods[16]. The horizontal sub-surface flow constructed wetlands (HSFCW) planted with *Typha Latifolia* and *Phragmites Australis* showed the removal of pesticide (terbuthylazine) from agricultural wastewater by 58% and 78%, respectively [18]. In cold climates, a hybrid constructed wetland designed to treat the dairy wastewater exhibited high removal efficiency of 70-96% for chemical oxygen demand (COD), 32-86% for Ammonium (NH_4-N), 39-90% Total Nitrogen (TN), and 70-93% Total Phosphorus (TP)[19]. A floating treatment wetland (FTW) with an anaerobic biofilter showed high removal efficiency for Total Coliform (99.9%), Turbidity (91%), and COD (71%) from urban wastewater[20].

Nevertheless, improper design, lack of operational and maintenance know-how, inadequate standard assessment protocols, and the general assumption that CW remains eco-friendly on its own, lead to a significant adverse effect on its performance and subsequent negative impact on the environment. Consequently, effective wastewater treatment and long-term sustainable operation of CW remains a challenge worldwide. Poorly managed CW can potentially contribute to environmental challenges such as greenhouse gas (GHG) emission, odor, and growth of invasive species[4,16]. Studies have shown that CW can be a possible source of GHG emissions such as methane (CH_4: 30 mg/m^2/hr to 450 mg/m^2/hr) and nitrous oxide (N_2O: 59 mg/m^2/hr to 1252 mg/m^2/hr) in two-year period[21]. The performance and the sustainability of the CW critically depend on several design parameters (i.e., surface area, water depth, hydraulic retention time and loading rate, and wastewater type), its operation, and regular maintenance (i.e., influent feeding mode, performance monitoring, and biomass harvesting). Therefore, in this chapter, an attempt has been made to comprehend the CW design techniques and related influencing factors for appropriate and efficient design. Furthermore, the operation and maintenance techniques were precisely discussed for the sustainable and long-term effective performance of CW.

Classification of Constructed Wetlands

Multiple design configurations of CW are reported and classified such as based on flow pattern (free-surface flow, and subsurface flow), type of vegetation (emergent, free-floating, and submerged), stages (single stage, multi-stage or hybrid system), type of feeding mode (continuous, and intermittent feeding), type of treatment (primary, secondary, and tertiary), and enhancement (artificially aerated, tidal flow, and baffled flow) (Luise Davis, 1996; UN-HABITAT, 2008; Wu et al., 2015; Rahman et al., 2020; Shukla et al., 2022). Principally, typical CW are classified based on wetland hydrology, and flow regime into two broad categories, (i) Surface flow (free surface also known as free-water surface CW), and (ii) Subsurface flow CW as shown in **figure-1** (Vymazal et al., 1998). Several CWs have been developed by merging the two or more to obtain the desired effluent quality. The combination of Free-water surface

CW (FWS) and various forms of Subsurface flow CW (SFCW) forms the third category of wetland, (iii) Hybrid CW (HCW) (Vymazal, 2018; Malyan et al., 2021).

The FWS constructed wetland consists of a shallow basin with impervious lining or permeable substrate or both to support the vegetation roots and the water flow control structure. The wastewater flows above the saturated substrate (e.g., gravel, sand). In FWS, the water flow is mainly regulated by aquatic macrophytes, low flow velocity, and water depth [17]. The surface layer of FWS remains aerobic and the deeper water layers are generally anaerobic therefore, they are frequently used to treat stormwater, and mine drainage[5]. FWS is low-cost, easy to maintain, and less prone to clogging than other CWs[20]. However, the decay of emergent vegetation, algal growth, litter, and cold climate often reduced the pollutant removal efficiency of FWS (Nuamah et al., 2020; Yadav et al., 2023).

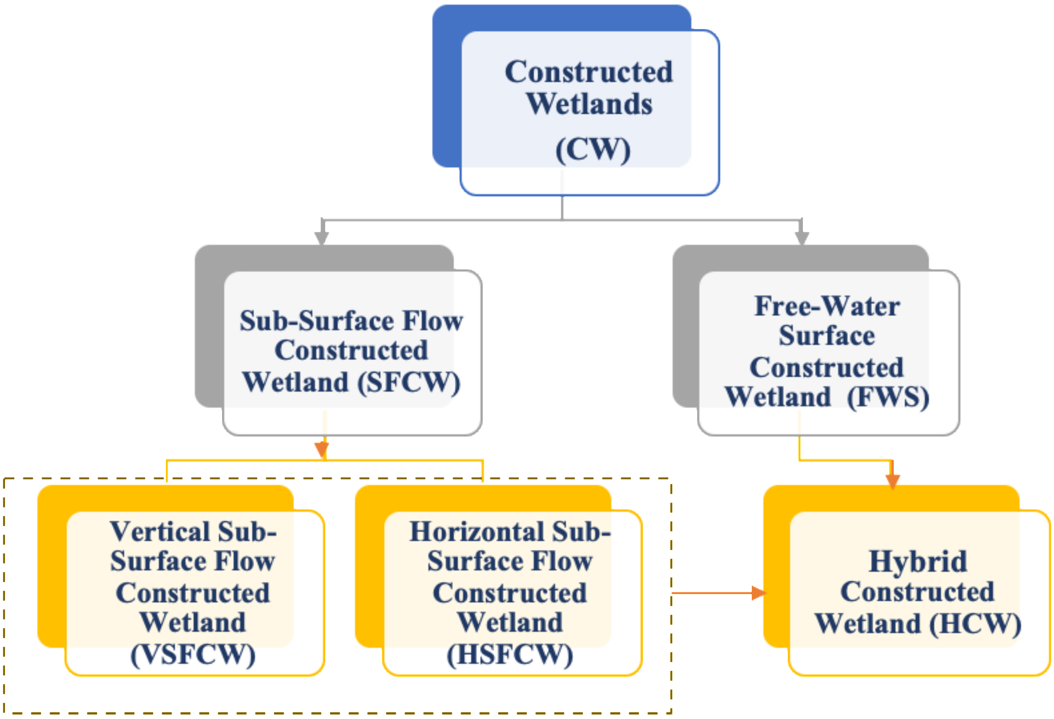

Fig. 1. Classification of Constructed Wetland based on wetland hydrology and flow regime.

On the other hand, SFCW consists of an artificially built basin with a seepage resisting material with porous substrate (sand, gravel, rock) and emergent vegetation through which wastewater flows either horizontally or vertically. The water level remains 10 to 15cm below the top surface of the SFCW therefore, minimize the pest, and odor problems [23]. The porous substrate acts as the filter media and provides a greater surface area for wastewater treatment contact than FWS thus, being efficient in removing a wide range of pollutants such as organic loads, heavy metals, nutrients, and suspended solids. Subsequently, SFCW shows enhanced assimilation capacity per unit area and is smaller than FWS for the same volume of wastewater. The system also has high tolerance to cold climate (Luise Davis, 1996; US-EPA, 2000; Shukla et al., 2022). However, SFCW has a relatively high per-unit construction cost than FWS. Owing to the hydraulic constraint posed by the substrate it can treat wastewater with low solid concentrations and at uniform flow conditions. Clogging in SFCW is mainly associated with solid accumulation due to high retention, microbial biofilm growth, and unmanaged vegetation[27]. The SFCW is further categorized based on the flow direction into, (a) vertical sub-surface flow CW (VSFCW where the effluents move vertically (up-flow or down-flow) through the substrate, and (b) horizontal sub-surface flow CW (HSFCW) where the effluent moves horizontally through the substrate. In general, HSFCW is used for the removal of BOD, and TSS and for enhanced denitrification due to limited oxygen transfer capacity. Conversely, VSFCW has greater oxygen transfer capacity and is used where nitrification is required (Crites, 1994; Luise Davis, 1996; Nuamah et al., 2020).

Hybrid CW (HCW) is a slightly complex combination of various forms of SFCW and FWS, used to enhance the pollutant removal efficiency, depending on the type of wastewater (Barrett et al., 2019; Vymazal et al., 2021). Studies have shown that the pollutant removal efficiency increases with an increase in design complexity in the order of HSFCW<VSFCW<HCW or intensified CW, however, difficult to maintain [29]. The most preferred combination used in studies is VSFCW-HSFCW followed by HSFCW-VSFCW. Contaminant removal efficiency increases per unit area of the hybrid treatment system even in the cold climate[19]. The combined system reduces the problem of nitrification and denitrification simultaneously making the HCW more efficient in pollutant removal and transformation[19,30,31]. Artificial aeration is required to maintain the dissolved oxygen in the CW as in most cases nitrification takes place when DO >1.5 mg/l and denitrification takes place at DO < 0.5 mg/l [23].

Design Criteria

The CW design configuration should be planned to take advantage of the natural topography. The design must be simple, easy to maintain, utilizing natural energies, and planned for extreme weather and climate conditions (e.g., storms, floods, and droughts) [32]. Principal criteria for CW design include site selection, water depth, vegetation selection, substrate selection, hydraulic loading rate (HLR), Hydraulic retention time (HRT), wastewater type, and its operation and maintenance (Table 1).

Table 1 Design criteria for FWS and SFCW for the desired effluent quality of BOD< 30mg/L and TSS <30 mg/L (Colares et al., 2021; Crites, 1994; Luise Davis, 1996; Millot et al., 2016; Shukla et al., 2022; UN-HABITAT, 2008; US-EPA, 2000; Wu et al., 2015; CPCB, 2019)

Design/Sizing Parameters	Equations	FWS	SFCW
Design Flow	Q_m or Q_{av}	Maximum or average flow	Maximum or average flow
Land Requirement (Population equivalent) in m^2/PE		-	0.8-3 (VSFCW) 5-10 (HSFCW)
Length(L): Width(W) or (Aspect Ratio)		>1:1 (plug flow hydraulics); 3:1 to 5:1	1:1 and 1:2; <3:1 [(L: 61m; W:12-30m (~15 m)]
Water Depth (m)	D_w	0.1 to 2 m; 0.6-0.9m (fully vegetated zone); 1.2-1.5 m (open water zones); 1m (inlet settling zone	0.3-1.5
Bottom Slope (%)	dh/dL	< 0.5%	0.5 to 1%
Hydraulic Retention Time (HRT) in (days)	V_w/Q_o [V_w = A*Dw*n]	2- 3 days or 5 to 30 days (climate dependent)	2 to 5
Hydraulic Loading Rate (HLR) in (m/day)	$C*V_w/A$	<0.1	<0.5
Inlet & Outlet structures		Uniform distribution and collection of influent and effluent	Uniform distribution and collection of influent and effluent
Substrate (Filter Media size)		<20 mm (porosity 0.3 to 0.5)	40-80 mm (inlet zone, outlet zone) 20-30 mm (treatment zone) 5-20 mm (top 10cm of planting media)
Vegetation		Locally available native species	Locally available native species

Note- L: Length; W: Width; dh/dL: Hydraulic gradient; V_w: Useable CW Water Volume or mean volume; Q_o: Average Outflow Flow Rate: (Inflow+Outflow/2); Q_m: Maximum flow; Q_{in}: Wastewater inflow; A: CW Surface Area; C: Parameter concentration; n: porosity.

Site Selection for CW

Selection of appropriate site for CW can save significant construction cost and prevent negative environmental impacts[12]. For sustainable and effective functioning of the CW, the critical factor for selecting the suitable site involves topography (slope), land use and soil layers, land availability, natural resources near the site, hydrology, and climatic conditions[5]. In principle, the site for the CW must be near the wastewater source to avoid lengthy conveyance and a low, flat area with a gentle slope is conducive for the gravity flow, reducing the cost of pumping and construction. However, the FWS flat area lowers the cost while the sloped area requires the construction of dikes or gradings. Ideally, the CW site consists of a soil layer with low permeability (< 10^{-6} cm/s) which acts as the barrier to minimize contaminant infiltration to groundwater. For soil with high permeability liners such as imported clay, asphalt and synthetic liners (PVC) must be used, which raises the construction cost[32]. Furthermore, it is essential to consider the depth of the aquifer, water from streams, and other drainage issues before site selection. It is recommended to avoid construction in floodplains or natural wetlands unless specific measures are required. Tournebize et al., (2013) found that off-stream CW enhances biodiversity with less areal requirement and better performance in pesticide removal than the in-stream CW. The performance of the CW is often limited by inadequate retention time which is limited by the size of the wetland. Therefore, the CW site must have adequate space or land available for construction[4]. Local climate and seasonal variations significantly affect the efficacy of CW.

Owing to the shallow depth, the open-to-atmosphere CWs are greatly influenced by rainfall, temperature, snowmelt, drought, and spring runoff. Change in temperature largely affects the microbial community in the CW. For instance, denitrification in CW reduces at a temperature <15°C while stops at 5°C affecting ammonia and nitrogen removal. Further, microbial activity significantly influences organic matter removal in the CWs and is dependent on temperature upto some extent[37]. Precipitation dilutes the pollutant, increases the water level, and reduces HRT whereas, evapotranspiration (ET) concentrates the pollutants in CW and increases the HRT. In general, ET in CW is reported to be 1.5 to 2 times the pan evaporation [32]. Singh and Chakraborty, (2022) reported that rainfall noticeably reduced the treatment of acid mine drainage in an unsheltered CW (sufate:50%, Fe: 85%, Al: 70%, Zn: 93% , Co: 82%, Ni: 83%, and Cr: 90%) than the sheltered CW (sulfate: 60%, Fe: 90%, Al: 79%, Zn: 94% , Co: 92%, Ni: 91%, and Cr: 96%) due to shortening of HRT and insignificant dilution. The first flow storm often carries the higher pollutants therefore excess runoff needs to be diverted from the CW to avoid runoff overflow. Selection of the site therefore requires the proper understanding of the climatic and seasonal variation for the effective functioning of the CW. The runoff due to precipitation needs to be estimated and included in the design flow.

CW Sizing: Governing Equations

In general design criteria involves areal loading rate ($g/m^2/d$), and volumetric loading rate ($g/m^3/d$). Many of the pollutant removal mechanisms in CW depend on the surface area theoretically, such as oxygen transfer, plant growth, and sedimentation therefore, areal loading rate ((influent flow rate*pollutant concentration)/surface area) is frequently used for the design[32]. SFCW can be calculated based on BOD, total nitrogen, ammonia nitrogen, etc. Typically, the P-K-C* first-order model has been used to estimate the design area of SFCW [39], and the first-order plug flow model is used for FWS assuming linear and areal kinetics [6,40].
EPA suggests the use of Darcy Law for the CW area and width estimation depends on the areal loading rate, water depth, flow, and hydraulic conductivity, assuming the laminar flow through the media [32], as given in **Equation 1**.

$$Q = KAS = KWD_w\left(\frac{dh}{dL}\right) \quad (1)$$

Where, K is hydraulic conductivity (m/d or m^3/m^2-day); Q is flow rate (m^3/day); A is cross-sectional area which is normal to flow given by Width (W)*Water Depth (Dw) in m^2, S is hydraulic gradient given by dh/dL. Hydraulic conductivity in the initial 30% remains 1/4 to 1/3 of the remaining 70% of the SFCW. The recommended bottom slope is 0.5 to 1% for easy maintenance and proper draining from inlet to outlet. The width of the CW system can be calculated using the Darcy law as in equation-1.
Several modifications have been made in different literature for estimating the CW area. UN-HABITAT, (2008) provides the surface area of the wetland based on influent and effluent BOD concentration (**Equation 2).**

$$A = \frac{Q(lnC_i - lnC_e)}{K_{BOD}} \quad (2)$$

where, A is surface area of bed (m^2); Q is average flow rate per day; C_i and C_e are the concentration of pollutants (mg/l) at the influent and effluent of the CW and K_{BOD} is the decay rate constant increases 10% at every 1 °C rise in temperature expressed as $K_T dn$ where K_T is given by **Equation 3**:

$$K_T = K_{20}(1.06^{T-20}) \quad (3)$$

Where, K_{20} is rate constant (at 20 °C/day), T is system temperature in °C, d is column water depth (m), and n is substrate porosity (%). K_{BOD} is generally higher in VSFCW than in HSFCW.

The design criteria of CW involve the maximum pollutant load (rate) to meet the discharge standard. While designing CW, the end-use of the treated wastewater needs to be considered. For instance, emphasis should not be on excessive nutrient removal when treated wastewater is used for irrigation where nitrogen (N) and phosphorus (P) are beneficial whereas, the same need to be efficiently removed before discharging it to the water bodies [39]. Land requirement for CW is often calculated based on the population equivalent (PE) for wastewater of uniform quality and quantity. Ilyas and Masih, (2017) reported the land requirement of HSFCW (5-10 m^2/PE) and VSFCW (1-3 m^2/PE). In Europe, the typical land requirement for CW is 1 to 3 m^2/PE (VSFCW) and 5 m^2/PE (HSFCW). For tertiary treatment, an areal requirement of 1 m^2/PE and for stormwater treatment 0.5 m^2/PE is recommended by Environment Protection Agency [32]. UN-HABITAT, (2008) recommends land requirement of 0.8 to 1.5 m^2/PE (VSFCW) and 1 to 2 m^2/PE (HSFCW). However, the small land requirement is often not suitable for nitrate removal, particularly in colder regions[23].

Water Depth

Water depth in CW is a critical factor influencing the system's functioning, vegetation growth, and biochemical reaction in the root zones by altering the redox status and dissolved oxygen (DO) (Vymazal et al., 2021; Singh et al., 2023). Species richness in the CW are directly linked with water depth.

Studies have suggested that the optimum water depth in SFCW should be equivalent to the maximum root depth as the plant root depth is critical for the removal of pollutants [22]. Nevertheless, plants with an abundant nutrient supply near the surface might not grow their roots deeper in the system. Better BOD removal was observed in the system with 45cm media depth than in the 18cm media depth, however, it is unclear about the effect of increased HRT due to increased depth[32]. Singh et al., (2022) showed the abundance of the bacterial community in the shallow cells of HSFCW (0.8 m) than in the deeper cells (1.5 m) such as aerobic denitrifiers, anoxic denitrifiers, heterotrophic nitrifiers, and phosphate accumulating bacteria influencing pollutant removal, however, nitrogen-fixing bacteria and nitrifiers were found missing in the shallow cells. This suggests the selection of water depth could be based on target contaminants and the different HRT required to remove or transform them. Millot et al., (2016) studied the treatment performance of CW at different depths and found that increasing depth beyond 0.27 m does not significantly influence the removal of TSS and COD except ammonium removal which increased (60%) with depth from 0.40 m to 1 m. Most of the COD removal occurs at first 0.20 m of depth. Typically, the recommended water depth is 0.1 to 0.7m for SFCW however, greater depths were suggested in other studies [39]. And for FWS the recommended depth is 0.6-0.9m (fully vegetated zone), 1.2-1.5 m (open water zone) [32]. In FWS, the water depth needs to be monitored, as over time with the accumulation of detritus, the water depth decreases.

Vegetation Selection

Macrophytes or wetland plants are one of the important components of CW design as they support several pollutant removal processes in the system such as uptake of nutrients, filtration in water column (FWS), reduce water velocity, platform for microbial biofilm development, transmission and release oxygen, provide habitation and supports biodiversity, more often prevent clogging of the treatment system (Kumar et al., 2019; Tang et al., 2019; US-EPA, 2000; Van De Moortel et al., 2010; Vymazal, 2013; Yadav et al., 2023). The selection of plants for CW design depends entirely on the type of wastewater to be treated and the availability and properties of plants. UN-HABITAT, (2008) recommended plant selection based on the availability of locally available plants, species with deep roots, rhizomes and large fibrous roots, good stem density and biomass for translocation of nutrients, and plants with sufficient oxygen release in the root zones. Plants tolerant to waterlogging and anoxic conditions and efficient in hyper-eutrophic situations with greater pollutant absorption capacity are recommended for CW design (Vymazal, Jan 2006; Vymazal, 2010; Wu et al., 2015). Contrarily, considering the limited contribution of plants in oxygen transfer (<2 mg/L) and nutrient uptake (12 to 120 g N/m^2/year) the selection of plants was suggested to be based on aesthetics, impact on CW operation, and feasibility in the given location [32]. Among the emergent, floating, and submerged vegetation, the emergent plants were commonly used in the FWS and SFCW [48,49]. Studies have indicated that the plant with higher biomass development has higher pollutant uptake potential which could be a criterion for plant selection. For instance, Pappalardo et al., (2017) studied the efficacy of seven different locally available plant species and found that the plant *Carex spp.* with high biomass (433 g/m^2) has high nitrogen uptake (4.8 g/m^2). Furthermore, not every plant species can tolerate the toxic pollutant load. Li et al., (2020) studied the toxic impact of perflourooctane sulfonate on the two plant species *Eichhornia crassipes* and *Cyperus alterniforius* in the VSFCW and found that at high concentrations the chlorophyll synthesis in the plants was inhibited whereas the leave membrane and cell structure was destroyed. The most commonly used plant species in CWs are *Phragmites sp.* and Typha sp. such as *Phragmites australis, Typha latifolia,* and *Phragmites karka* which have rapid growth, high biomass, and are tolerant to variable climatic conditions [34]. Other commonly used vegetation species are *Typha augustifolia*, *Typha domingensis, Scirpus validus*, *Scirpus lacustric L*, *Juncus effuses*, *Juncus, articulates*, *Eleocharis sphacelate*, *Cyperus papyrus*, *Canna indica* (Vymazal, 2013; Yadav et al., 2023; Nan et al., 2023).

Substrate Selection

Substrate selection is crucial for the CW's effective functioning as it provides media for plant growth, surface area for pollutant absorption and adsorption, and aids in filtration [53]. The pollutant exchange, precipitation, adsorption, and complexation are the main processes through which pollutant removal and transformation occur in the CW system [3]. The availability and the cost of the substrate usually determine the substrate selection. A substrate with low adsorption capacity often hampers the pollutant removal efficiency in CW whereas a substrate with low hydraulic conductivity could lead to system clogging further reducing the CW performance. The substrate with high hydraulic conductivity enhances the phosphorus sorption capacity of the CW and avoids short-circuiting [27]. Therefore, adsorption and hydraulic permeability are important properties of substrate for its selection. In FWS, the use of loose soil with high humic content, and the use of loam, silt, and sand promote the plants growth, and rapid biomass generation [32]. In general, the other substrate selection criteria involve physical factors such as particle size, shape, surface area, porosity, and hydraulic conductivity; chemical factors such as toxicity, and chemical stability; and biological factors such as electron acceptor and electron donor [53]. Particle size of the substrate influences its porosity, and hydraulic conductivity. For instance, fine-sized substrate often enhances pollutant removal efficiency, however, due to filtration and accumulation of the pollutants they are highly susceptible to clogging. UN-HABITAT, (2008) recommends the use of rounded substrate over sharp-edged substrate as the round shape provides loose packing and not damaging the plant roots. In SFCW, the recommended size of the substrate at the inlet/outlet zone is 40-80 mm while at the treatment zone, it is 20-30mm [5]. Essentially, the substrate must have a long life, should not lead to any secondary pollution such as the leaching of toxic heavy metals causing adverse environmental impact, and must be disposed of safely whenever required. Commonly used natural substrates that are easily available, low cost, and have effective pollutant removal efficiency are soil, sand, gravel, and rock. Singh et al., (2023) used gravel substrate in the HSFCW for the treatment of domestic wastewater and obtained 89 to 91% of organic load removal, 67 to 72 % of nutrient removal, and 53% of phosphorus removal. Phosphorus removal can be enhanced by the substrate with calcium (Ca), Iron (Fe), and aluminum (Al) content such as limestone, alum sludge, and slag. Other substrates such as compost, rice husk, and peat can be used to remove the nitrogen and organic load in CW. Mixed substrates such as strate gravel, and vermiculite provide reactive surfaces for microbial growth and aid in removing water with low nutrients [27]. Biochar formed by the pyrolysis process (biomass) has a high surface area and enhances pollutant removal in CW [3]. Furthermore, the use of biochar, zeolite, and gravel reduces the N2O emission from CW [16].

Hydraulic Loading Rate and Retention Time

The hydraulic capacity of the CW is principally indicated by the hydraulic loading rate (HLR) and hydraulic retention time (HRT). Hydraulic capacity is crucial for designing, and effective functioning of the CW. HLR signifies the maximum loading of the pollutants in the CW per unit area for a specific time (days), and governs the planning as well as designing of the treatment system (García et al., 2005). While HRT is the average time the wastewater retained or remained within the CW also indicates the contact time with the substrate, microbial biofilm, and the plants. At higher HRT the contact time of the wastewater with the microbial community increases which further increases the removal efficiency of the contaminants or parameters needing higher HRT (Romain et al., 2015; Shukla et al., 2022). On the other hand, increased HLR reduces the contact time through quick flow of wastewater within the system [34,47,55–57]. García et al., (2005), found that with increase in HLR concentration of COD and BOD increases in the effluent from the HSFCW. Studies have shown that nitrate removal enhanced with an increase in HLR upto 1.5 m/day and at an HRT of 2 days, however further increase in HLR reduces the nitrate removal efficiency [58]. In general, optimum HRT is largely influenced by the optimum HLR for the treatment system. At HLR (75 -100 L/day) and high HRT (>3 days) leads to increased plant density in the CW compared to lower HRT (1-2 days) and HLR (150-300 L/days) (Millot et al., 2016; Wu et al., 2015). In some studies, different HLR was suggested for variety of wastewater and for different treatment systems such as for the treatment of domestic wastewater the optimum HLR remains 0.1 m/day (FWS), 0.36 m/day (VSFCW), 0.46 m/day (HSFCW) and 0.3 m/day (HCW), for industrial wastewater the HLR remains 0.1 m/day (FWS), 0.57 m/day (VSFCW), and 0.59 m/day (HCW) (Li et al., 2018; Shukla et al., 2022). Longer HRT reduces the peak of the pesticide concentration in the vegetated cell by 91 % at

HRT of 330 min, than the cell with HRT of 280 min (89% reduction in peak) [60]. Akratos and Tsihrintzis, (2007) studied the impact of various HRT (6, 8, 14, and 20 days) on the pollutant removal from HSFCW and found that removal efficiency of organic matter, TKN, and phosphate enhanced at the 8-day HRT. Furthermore, mercury (Hg) removal in planted CW cells increased from 50% to 95% with an increase in HRT from 6 hours to 24 hours indicating that the longer HRT increases the removal efficiency of Hg [61].

Operation and Maintenance

Feeding Mode

The performance of CW is substantially influenced by the feeding mode such as continuous feeding, batch, or intermittent feeding [22]. The contaminant removal in CW largely depends on the oxidation and the reduction potential in the system which is further influenced by the mode of operation (batch or continuous)[27]. For instance, the system with intermittent feeding mode provides an oxidized environment conducive for ammonia removal whereas continuous feeding mode supports redox zone for sulphite removal. In batch or intermittent-fed mode, the system is alternatively flooded and drained resulting in the air entrainment in the substrate (soil or gravel) pores. The air in the substrate pores enhances the oxidation of carbon (C) and Nitrogen (N) in the CW than in the continuous feeding mode, thus enhancing the overall performance of the system in batch feeding mode [4]. Caselles-Osorio and García, (2007) studied the impact of intermittent feeding and continuous feeding on the removal efficiency of HFCW and found that the ammonia removal enhanced significantly (average range: 80 to 99%) in intermittent feeding mode (range: 0.58 to 0.67 g N/m^2 day) than in the continuous feeding mode (range: 0.52 to 0.58 g N/m^2 day). Moreover, the sulphate removal efficiency was found to be higher (average: 76 to 79%) in the continuous feeding mode (51 to 58%). Zhang et al., (2012) studied the impact of intermittent feeding and continuous feeding on the removal of eight pharmaceuticals namely, naproxen, ibuprofen, diclofenac, carbamazepine, caffeine, clofibric acid, salicylic acid, and ketoprofen in the mesocosm-scale CW. The study found high removal efficiency in the intermittent-feeding mode for almost all the pharmaceuticals except naproxen, carbamazepine, and clofibric acid. The intermittent-feeding mode enhances the atmospheric transfer, improves the CW substrate characteristics, and mass transfer mechanism thus enhancing the contaminant removal efficiency of CW (Nuamah et al., 2020; Wu et al., 2015).

Clogging Control

FWS are low-cost, easy to maintain, and less prone to clogging than other CW [20]. Clogging in SFCW is mainly associated with solid accumulation due to high retention, microbial biofilm growth, and unmanaged vegetation [27]. Poor hydraulic conductivity and reduced porosity lead to clogging of the CW and performance decline, this further reduces the designed life of the system [27]. The degree and distribution of clogging in the system depend on the hydraulic behavior and solid accumulation, respectively. Pedescoll et al., (2013) studied the impact of hydraulic loading rate on clogging and found a solid accumulation rate of 0.31 kg/m^2 for TSS and 0.08 kg/m^2 for BOD at the HLR of 50 mm/day and 100 mm/day, respectively. Plant species such as *Typha latifolia* and *Typha augustifolia* produce high biomass whose litter and decayed leaves could clog the system if biomass harvesting is untimely [23]. The below-ground biomass of the *Typha augustifolia* is two times more than the *Phragmites australis* thus developing clogging in the system. The presence of plants and organic load results in the loss of hydraulic conductivity by 20% and 10% [56]. The CW system with soil and sand substrate (small diameter media) is often prone to clogging than the other substrate resulting in ponding (overflowing in SFCW) and reduction in removal efficiency. It is recommended to use the substrate of 40mm and 80mm at the inlet and outlet zones to minimize clogging. Furthermore, the length of the inlet and outlet zones should be 2m and 1m, respectively for even distribution and collection of influent and effluent without clogging (Luise Davis, 1996; US-EPA, 2000). Selection of appropriate filter media or substrate and proper design of the CW is essential to avoid clogging of the system.

Plant Biomass Harvesting

The CW plants are crucial for the effective functioning of the system. Most of these plants are self-maintaining, they grow, die, and then regrow every year. Harvesting of plants is largely site-specific and depends on the objective of the CW. However, periodic biomass harvesting is required to maintain the desired plant community, enhance hydraulic capacity, prevent mosquito breeding within the CW and remove the undesired species [24,32]. Unwanted harvesting may disturb the CW performance. A well-designed and operated system may not require regular biomass harvesting. The constant load of pollutants in the wetland affects the diversity of the plant species and is sometimes toxic to plants leading to their die-off and decay in the system further increasing the nutrient load within the treatment system (Luise Davis, 1996). Contaminant removal within the plants can be done through absorption, microbial degradation (biofilm development), and plant uptake. In general, the uptake of the plant is not permanent; once they die, they release back the pollutants thus reducing the efficiency of the system. Biomass harvesting may increase the cost but aid in nutrient removal from the system. Furthermore, high biomass plants such as *Typha Latifolia* can also cause clogging of the CW system, therefore routine harvesting is required to maintain the growth [23]. Plant harvesting enhances the growth of the plant and their contaminant removal efficiency. In some cases, harvesting plants such as *Phragmites* at the end of the growing season reduces the N and P (US-EPA, 2000). However, for metal removal, the suggested harvesting period is the beginning of senescence and the end of the growth period, depending on the quantity of metal uptake [12].

Concluding Remarks

Appropriate design, regular operation, and maintenance ensure the enhanced performance and sustainability of the CW for wastewater treatment. The design criteria vary with location and must always be site-specific. The use of locally available materials is highlighted for ease of construction and cost-efficiency. A well-designed treatment system requires less maintenance than a poorly designed system. Constructed wetlands for wastewater treatment are expected to change rather quickly than the natural wetlands due to the continuous accumulation of pollutants, plant litter, and sediment. Species diversity further increases with the increase in maturity of the system. It is recommended to maintain species diversity if the habitat perspective is valued. However, if the habitat value is not crucial and the treatment performance is acceptable, the change in species diversity is recommended to remain undisturbed. Any ecosystem terrestrial or aquatic has the limited capacity to tolerate the disturbance. High wastewater load can hamper the performance of the constructed wetland which is largely due to the accumulation of the sediment and pollutants in the substrate of the constructed wetlands. Therefore, periodic monitoring is recommended to collect the evidence of stress in the system and take the necessary remedial action on time for the long-term operation of the constructed wetland system.

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Wetlands: Role in Water Management

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Introduction

Wetlands are transition zones between terrestrial and aquatic ecosystems. Although wetlands are an established concept, differences in size, location, duration of flooding, species hosted, and degree of management have led to lack of agreement on a single scientific definition. Wetlands are one of the three major ecosystems on Earth and are found on every continent, with an estimated global area of around 12.1106 km^2. Wetlands are multifunctional systems performing as nature-based solutions (NBS) for water management. Wetlands may remove or reduce a number of organic and inorganic pollutants (e.g., nutrients, heavy metals, hydrocarbons, pesticides) by different physical, chemical, and biological processes developed between vegetation, microorganisms, soil/growth substrate, and water. They have proven to be efficient and effective in improving the quality of water from different sources, such as runoff from agriculture and urban areas, and domestic and industrial wastewater.

Wetlands worldwide are threatened by anthropogenic and natural drivers, such as changes in land use (conversion to agricultural land, urbanization), water use and availability, and climate change, including sea level rise and impacts of extreme events (i.e., floods and droughts) and warming. They are also threatened by a variety of degradation processes, such as increased pollution loads. Furthermore, wetlands globally have been fragmented by human activities (e.g., land drainage), leading to reductions in the connectivity needed to maintain the integrity of ecosystem functioning. Globally, wetland area has declined by 87% since 1700, by 64–71% since 1900, and by 35% since the 1970s.

The role of wetlands in water management has received increasing attention over the past few decades. Sustainable water management has become an urgent challenge due to irregular water availability patterns such as more frequent and intense hydrometeorological extreme events and water quality issues (eutrophication, increasing wastewater), driven by both anthropogenic and climate changes.

Types of Wetlands

- Marine/ Coastal Wetland
- Inland Wetlands
- Human made Wetlands

Role of Wetlands in Water Management

Wetlands are multifunctional systems performing as nature based solutions (NBS) for water management. The natural and constructed wetlands potential to support the regulation of hydrological fluxes and water quality. Wetlands can modulate peak flows by storing runoff and slowly releasing it over time, with positive impacts on soil moisture.

Disaster risk reduction

Wetlands act as buffers during floods, absorbing excess water and reducing flood risks in surrounding areas. Their ability to store water also ensures a steady water supply during dry seasons, benefiting both humans and wildlife.

Wetlands in improving water quality

Wetland processes remove suspended and dissolved solids and nutrients from surface and ground water and convert them into other forms, such as plant or animal biomass or gases. Debris and suspended solids (fine sediment or organic matter) may be removed by physical processes, such as filtering and sedimentation. When runoff and stream flow passes through wetlands before entering into a water body, nutrients may be taken up by wetlands plants and accumulate in less harmful chemical forms. Wetlands are so effective in removing excess nutrients from water. Many municipalities have built up wetlands for treating effluents from secondary treatment plants.

Nutrient cycle in wetlands

Wetlands are often described as “filtering out” pollutants from water, acting as “nature’s kidneys.” While this is a useful basic way to conceptualize it, there’s actually a lot more going on in a wetland than that. I usually explain to landowners that wetlands are very complex systems, and they don’t take nutrients out of incoming waters in just one way. Wetlands are able to remove nitrogen and phosphorus through a combination of physical, chemical, and biological processes. These naturally occurring processes adsorb/absorb, transform, sequester, and remove the nutrients and other chemicals as water slowly flows through the wetland. The main physical processes of nutrient removal are particle settling (sedimentation), volatilization (releasing as a gas into the atmosphere), and sorption. Sorption includes a nutrient adhering to a solid (adsorption) or diffusing into another liquid or solid (absorption). Chemical processes include transformations of nutrient forms and chemical precipitation, in which a solid compound is formed out of a liquid through a chemical reaction. The main biological processes are uptake (or assimilation) by plants, algae, and bacteria and transformation processes conducted by microbes. All of these processes occur throughout the different wetland compartments, which include water; biota (plants, algae, and bacteria); litter; and soil.

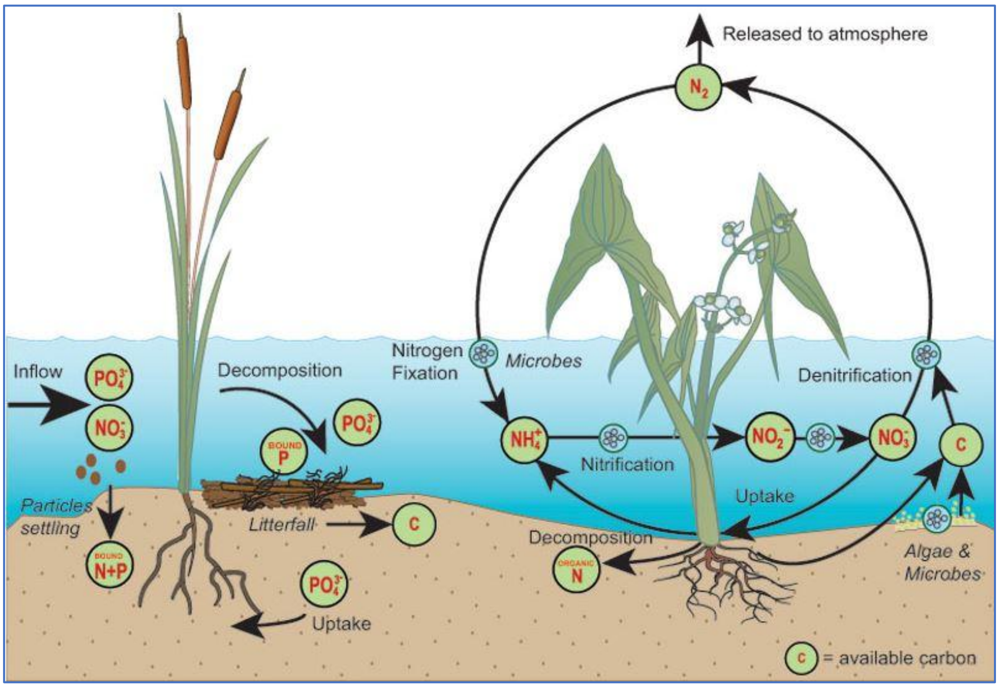

Fig 1: Nutrient cycle in wetlands

Both nitrogen and phosphorus can be present in many forms (particulate, dissolved, organic, inorganic, etc.), and these forms are acted upon differently by the various processes within the wetland compartments. For example, some forms are volatile and released into the atmosphere, others fall to the bottom of the wetland, and other forms are used by plants and microorganisms. These wetland processes are affected by the presence or absence of oxygen, season, temperature, water inflow rate, nutrient loading rate, and retention or holding time of the water within the wetland. So, while a wetland is always working to remove nutrients, the rate of this removal depends on a great variety of factors.

Ground water replenishment

Groundwater deficits are now significant problems in many countries, including China, India, the USA and the Arabian Peninsula, raising fears for drinking-water supplies and food security, as well as for the well-being of wetland ecosystems and the human livelihoods, plants and animals that depend on them. Wetlands plays crucial role for ground water replenishment.

Biodiversity conservation

Wetlands are biodiversity hotspots, supporting a wide range of plant and animal species. They provide habitat for migratory birds, fish, amphibians, and numerous other wildlife species. The diverse vegetation in wetlands helps in carbon sequestration, mitigating climate change impacts. Preserving wetlands is crucial for safeguarding biodiversity, preventing species Apart from their ecological importance, wetlands also offer significant economic benefits. They support fisheries, agriculture, and tourism industries, providing livelihood opportunities for local communities. Wetlands contribute to soil fertility, agricultural productivity, and natural resource sustainability. Protecting and restoring wetlands can lead to long-term economic gains while ensuring environmental resilience's, and maintaining ecological balance.

Regulating water flow in rivers and streams

Wetland acts as a regulatory system for river to control the flow of rivers and streams. Wetlands function as natural sponges that trap and slowly releases surface water, rain, snowmelt water and flood water. Trees, root mats and other wetland vegetation also slow the speed of flood waters and distribute them more slowly over the floodplain. This combined water storage an braking action lowers flood heights and reduces erosion. The holding capacity of wetlands helps control floods and prevents water logging of crops.

Threats to Wetlands

Despite their importance, wetlands face numerous threats, including habitat loss, pollution, and climate change. Urbanization, agriculture expansion, and infrastructure development often lead to wetland degradation and loss. Pollution from industrial runoff, agricultural chemicals, and waste disposal further jeopardizes wetland ecosystems. Climate change exacerbates these challenges, with rising temperatures and altered rainfall patterns affecting wetland health.

- Anthropogenic pressures
- Rapidly expanding human evolution
- Development projects
- Improper use of watershed
- Converting floodplains to aquaculture
- Planting trees on bogs
- Draining marshes for agriculture
- Forestry and urban development

- Mining them for peat

Conservation and Restoration Efforts

Efforts to conserve and restore wetlands are essential for their long-term sustainability. Governments, NGOs, and local communities collaborate to protect wetlands through designated conservation areas, regulations, and restoration projects. Wetland restoration involves habitat rehabilitation, water quality improvement, and invasive species management. Public awareness, education, and community engagement are also vital for promoting wetland conservation. Government of India taken up measure to conserve and protect the wetlands.

National Wetland Conservation Programme (NWCP)

National Wetland Conservation Programme (NWCP) was initiated by the Government of India during the year 1985-86 with the primary objective of conserving wetlands to prevent their further degradation. For conservation of lakes and wetlands, Ministry of Environment, Forest & Climate Change has been implementing two separate Centrally Sponsored Schemes (CSS), namely the National Wetlands Conservation Programme (NWCP) and the National Lake Conservation Plan (NLCP).

- **Identification and Assessment:** The program involves the identification and delineation of wetlands across India. This process includes surveys and scientific assessments to categorise wetlands based on their ecological, hydrological, and socio-economic significance.
- **Conservation and Management:** Once identified, the wetlands are subjected to conservation and management measures to prevent degradation. These actions include habitat restoration, controlling pollution, and managing water resources sustainably.
- **Capacity Building:** The program emphasises capacity building at the local, state, and national levels. Training and awareness programs are conducted to involve local communities and stakeholders in wetland conservation efforts.
- **Research and Monitoring:** Ongoing research and monitoring activities are crucial for understanding the dynamic nature of wetlands and assessing the effectiveness of conservation measures.
- **Legal Framework:** The NWCP supports the development and enforcement of legal and policy frameworks for wetland conservation and protection.

National Lake Conservation Plan (NLCP)

- Since 2001, the Ministry of Environment and Forests has been implementing the National Lake Conservation Plan (NLCP) to conserve and manage polluted and degraded lakes in urban and semi-urban areas.
- An integrated scheme, NPCA, combining the National Lake Conservation Plan and the National Wetlands Conservation Programme was created to avoid overlap, promote better synergies, and ensure conservation and management work.
- The new scheme will include conservation and management of lakes and wetlands in the country, including an inventory and information system on lakes and wetlands, a national level directive on lake and wetlands criteria, a regulatory framework, capacity building at the state government and local body levels, evaluation, and so on.
- Its goal was of conserving aquatic ecosystems (lakes and wetlands) through the implementation of long-term conservation plans governed by uniform policy and guidelines.

National Plan for Conservation of Aquatic Eco-systems (NPCA)

The National Plan for Conservation of Aquatic Eco-systems (NPCA) is a program for wetlands and lakes that promotes conservation. It was created by combining the National Lake Conservation Plan and the National Wetlands Conservation Programme. It is a centrally-sponsored scheme that is now being carried out by the Ministry of Environment, Forest and Climate Change (MoEFCC). In accordance with the criteria and available funds, the central aid is based on submissions from state governments.

- The NPCA strives for the comprehensive conservation and restoration of lakes and wetlands.
- The primary goal is to achieve significant improvements in water quality, enhance biodiversity, and restore ecosystems.
- The approach is integrated and multidisciplinary, operating under a common regulatory framework.

Conclusion

Wetlands are indispensable ecosystems with significant ecological, economic, and social value. Recognizing the importance of wetlands in water management, biodiversity conservation, and sustainable development is crucial for informed decision-making and effective conservation strategies. By prioritizing wetland conservation, restoration, and wise use, we can safeguard these vital ecosystems for future generations and ensure a healthier planet for all.

Treatment Mechanism in Constructed Wetlands

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Constructed wetlands (CW) provide a sustainable treatment technology due to their cost-effective treatment for the removal of organics and nutrients and low energy requirements. The treatment process utilized is similar to natural wetlands involving a plant-microbe-wastewater crosstalk. However, the large land requirement is a common problem, especially in dense cities, that limits the usage of CWs in urban settings compared to other conventional treatment technologies. If the land requirement is the major aspect of deciding the wastewater treatment system, then the activated sludge (0.2–0.4 m^2 per population equivalent), trickling filters (0.3–0.7 m^2 per population equivalent) or up-flow anaerobic sludge blanket reactors (0.05–0.4 m^2 per population equivalent) become more competitive options. Thus, strategies to reduce the land area requirement in constructed wetlands are the need of the hour. One such promising approach is increasing the depth of the constructed wetlands. Increasing the depth of the CWs to 2.0 -2.5 m leads to better utilization of the available land area as compared to conventional wetlands which have a depth of around 1.0- 1.5 m. Our studies have indicated that the organics removal is unaffected whereas the nitrogen (Rampuria et al., 2020) and phosphate removal (Verma et al., 2022) is higher in deep CWs due to the simultaneous availability of oxic and anoxic stretches within the same system.

Organics Removal in deep wetlands

The removal of organics in CWs is mainly carried out by heterotrophic microorganisms. Due to the aerobic nature of these microorganisms, Vertical flow (VF) CWs which operate with fill and drain cycles are considered more efficient in organics removal. Our primary analysis on deep VFCWs treating domestic and hospital wastewater has indicated that the areal removal rates are proportional to the loading rates until a saturation level is reached which is around 170 g / m^2 per day for domestic CW (Rampuria et al. 2021). Practically, in most of the VFCWs (n=82) being operated around the world, this limit is never reached, in fact, they are being operated in the low range of loading rate (Fig 1), suggesting that the depth of the CWs can be increased without affecting the removal rates per unit volume.

Nitrogen removal in deep CWs

The main forms of nitrogen in the CWs are organic nitrogen, ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-). Nitrogen in gaseous form may also exist as dinitrogen, nitrous oxide, nitric oxide, and ammonia. In CWs, nitrogen is continually transformed back and forth into inorganic

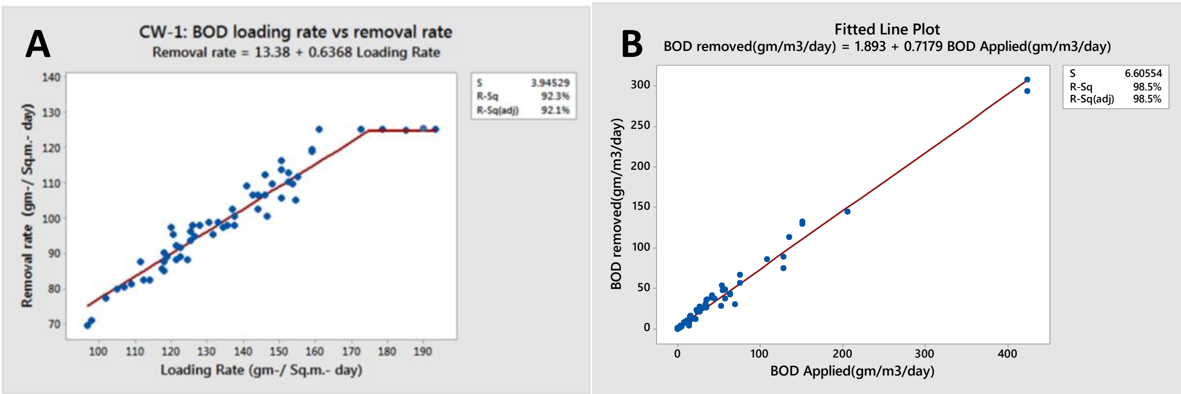

Fig 1. Variation in areal removal rate of BOD with the applied loading rate in Deep CW treating domestic wastewater (A); Variation in volumetric removal rate with the applied rate in 82 VFCWs treating domestic wastewater (Rampuria et al. 2020; Verma 2021)

and organic forms. The main nitrogen transformation processes being volatilization of ammonia, nitrogen fixation, mineralization, nitrification, denitrification, uptake by plants, sedimentation and adsorption. The major routes of nitrogen removal in CWs are given in Table 1.

The most widely understood pathway of nitrogen transformation in wastewater treatment systems is the conventional autotrophic nitrification followed by anoxic denitrification. This process suffers from some disadvantages as outlined in Fig 2. Discovery of novel microbial routes for nitrogen transformation in the recent times have led to development of novel treatment systems by tweaking the process parameters in favour of these microorganisms. These include use of Heterotrophic nitrifiers, aerobic denitrifiers (HNAD), sulfur oxidizing autotrophic denitrifiers (SOAD) and ANNAMOX bacteria. These alternative nitrogen removal processes offer significant advantages over conventional nitrification-denitrification for wastewater treatment like low sludge generation, low carbon requirement and reduced cost. The unique redox environment available along the depth of the deep CWs allow them to harbor bacteria belonging to different redox requirements within the same system. There has been increasing evidence through culture based and metagenomic analysis that the bacterial genera able to carry out these transformations are present deep CWs (Rampuria et al., 2021; Soti et al., 2024). Thus, with some design and process modifications, CWs can be used for efficient nitrogen removal along with the BOD removal at minimal additional cost.

Table 1: Nitrogen removal process occurring in CWs

Process	Transformation	Comments	Authors & Year
Volatilization	Ammonia-N (aq)→Ammonia-N(g)	Volatilization of ammonia can result in nitrogen removal rates as high as 2.2 g N m^{-2} d^{-1}.	Xu et al., (2023), Stowell et al. (1981)
Ammonification	Organic-N → Ammonia-N	The optimal pH and temperature for ammonification lie between 6.5-8.5 and 40-60º C respectively Range of ammonification rates (0.004 and 0.53 N m^{-2} d^{-1})	Yan et al., 2022; Vymazal 2007 Tanner et al. 2002
Nitrification	Ammonia-N → nitrite-N→ nitrate-N	Optimum temperature (30 to 40 °C), pH (6.6 to 8.0)	Vymazal 2007; Yang et al., 2021
Heterotrophic Denitrification	Nitrate-N → nitrite-N → gaseous N_2, N_2O	Occurs under low oxygen conditions (DO < 0.3 mg/L) Optimum pH range (6-8), Redox potential (+350 to +100 mV)	Lee et al., 2009 Vymazal, 2007 Yang et al., 2023
Heterotrophic nitrification aerobic denitrification	Ammonia-N → nitrite-N→ nitrate-N Nitrate-N → nitrite-N → gaseous N_2, N_2O (in the presence of oxygen)	pH: 6–9; High DO condition (3–6 mg/l), High C/N ratio (8–10), Can tolerate high NH_4^+-N load (~1000 mg/l)	Rampuria et al. 2021
Plant/microbial uptake (assimilation)	Ammonia-, nitrite-, nitrate-N→ organic-N	Only a small portion of the total N load is practically removed (up to 4-5%) by plant uptake in VFCWs	Kulshreshtha et al. 2022
ANAMMOX (anaerobic ammonium oxidation)	Ammonia-N + NO_2^- → gaseous N_2	Significant cost reduction about 60% and lower CO_2 emissions.	Kartal et al. 2012
Sulfur driven autotrophic denitrification	Sulfide/Thiosulfate/Elemental sulfur + nitrate/nitrite →sulfate + N_2	Optimum temperature 25-35 °C, nitrate concentration of more than 670 mg N/L is	Soti et al., 2024

		inhibitory; S/N ratio of 2.9 g S/g N is required

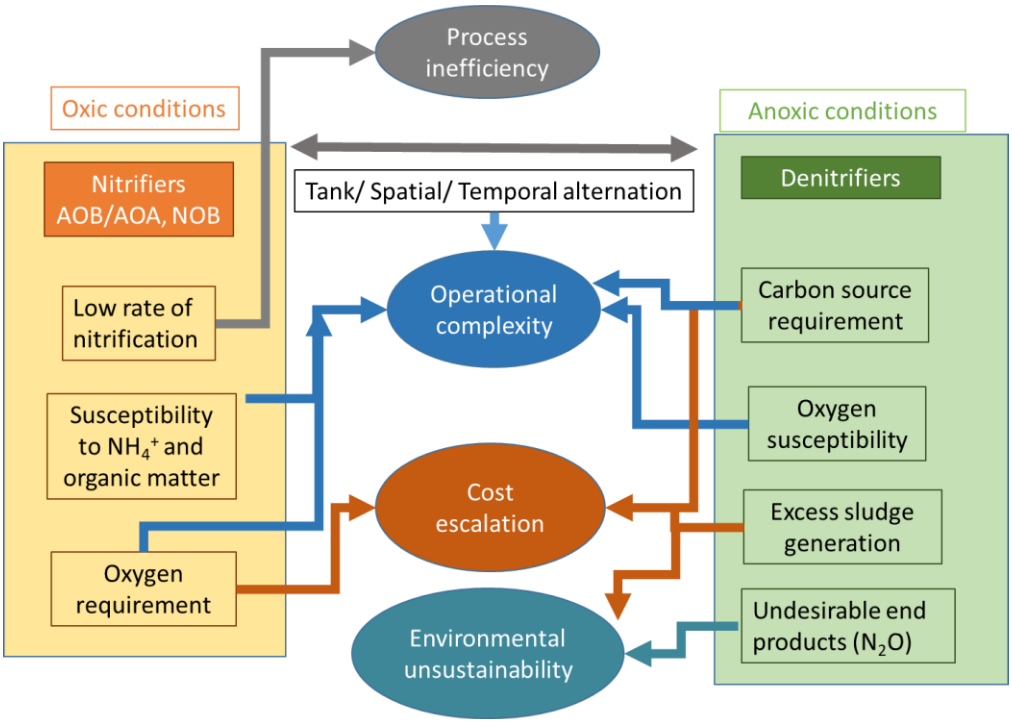

Fig 2. Limitations of traditional nitrification – denitrification reaction (Kulshreshtha et al. 2022)

Removal of phosphorous in deep CWs

Inefficient phosphorous (P) removal is one of the major issues of concern in conventional sewage treatment systems. Unlike their organics and nitrogen removal capacities, the potential of CWs as a sink for phosphorous is still debatable. The mechanisms of phosphorous transformations in CWs are given in Table 2. Our analysis on the secondary data from several CWs treating domestic sewage revealed that the removal rates of PO_4^{3-}-P conform to a linear positive relation with the loading rates (Verma et al., 2022). Further, the increased depth of the wetland appears to favor phosphate removal. PO_4^{3-}—P removal was found to be correlated with outlet dissolved oxygen, total Kjeldahl nitrogen removal and effluent nitrate. Thus, proper design, optimal organic loading and suitable pre-treatment may increase the applicability of CWs for phosphate removal from domestic wastewater. Larger area requirements can also be avoided by increasing their depth while keeping the volume of the filter media the same. The microorganisms responsible for the uptake/accumulation of phosphorous are Phosphate accumulating organisms (PAOs) (Table 2). PAOs have been utilized for Enhanced biological phosphorous removal by alternating anaerobic and aerobic/anoxic conditions. As phosphate is assimilated only in the soluble orthophosphate (PO_4^{3-}) form, the assimilation is enhanced in the presence of Phosphate Solubilizing Bacteria (PSB). These bacteria can convert insoluble phosphates into soluble forms. The spatial and temporal alternating oxygenation conditions prevailing in deep and intermittent flow CWs, respectively, can be gainfully exploited for enhanced phosphate uptake. Anaerobic digestion prior to CW treatment may also lead to enhanced phosphate removal by generating the volatile fatty acids (VFAs) required in the aerobic phase of PAOs

Table 2. Mechanisms of Phosphorous removal in CWs

Process	**Major findings**	**Authors & Year**
Adsorption	➢ Dependent on availability of adsorption sites which are plenty when the wetland first becomes operational and then decrease as the system approaches steady state	Vohla et al., 2011
Chemical precipitation	➢ The predominant form of P in wastewater effluent is anionic. Phosphate ions are reversibly interchanged between the liquid wastewater and the solid ion exchanger, offering simultaneous removal and recovery ➢ Proves difficult due to the relatively low abundance of phosphate ions in wastewater effluents, compared to competing species	Martin et.al., 2009
Plant uptake	➢ Usually low and is limited by the maximum density of plantation permitted	Maucieri et al, 2020
Microbial Uptake	➢ Microorganisms responsible for this uptake/accumulation are **Phosphate accumulating organisms (PAOs)** ➢ PAOs have been utilized for enhanced biological phosphate removal by alternating anaerobic and aerobic/anoxic conditions ➢ The assimilation is enhanced by the presence of **Phosphate Solubilizing Bacteria (PSB)** in soil that are able to convert insoluble phosphates into soluble forms	Blackall et al., 2002 Dorofeev et al., 2020

Removal of ARB in deep CWs

The mechanisms of removal of indicator and pathogenic bacteria in constructed wetlands include predation, filtration, sedimentation, adsorption, aggregation, natural die-off due to extreme temperature, toxins from plants and other microorganisms, unfavorable water chemistry, oxidative damages, and biofilm interaction. In addition, the influent water characteristics—presence of stressors—also greatly influence the fate of bacteria (Rampuria et al. 2021). As the conditions prevailing in deep CWs are quite different from shallow wetlands, they offer enhanced nutrient removal. In addition, they also exhibit efficient removal of fecal indicator bacteria and a comparable or even better removal of antibiotic-resistant bacteria as compared to conventional STPs (Rampuria et al., 2021, Fig 3).

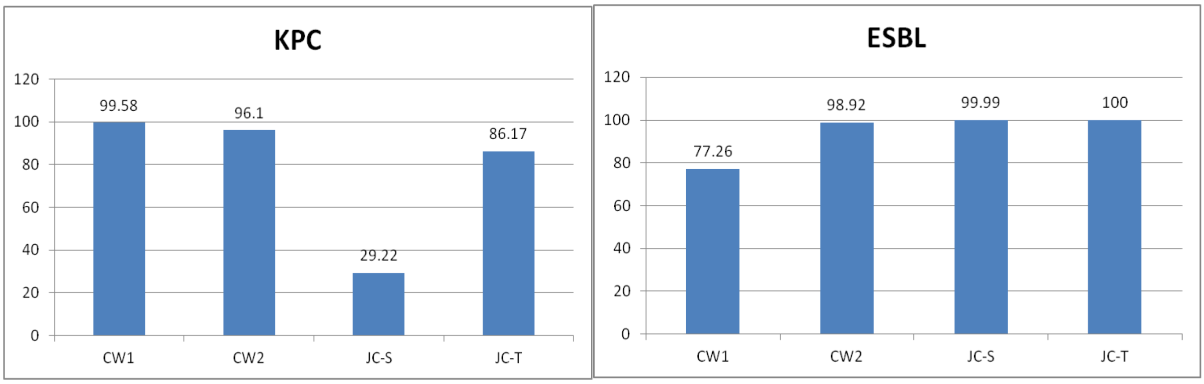

Fig 3. Percentage removal of antibiotic resistant bacteria in Urban (CW1) and Periurban (CW2) wetlands treating domestic and hospital wastewater respectively KPC *K. pneumoniae* Carbapenemase, ESBL- Extended spectrum beta lactamase (Rampuria et al. 2021)

To conclude, combined with a reduced land requirement and their ability to remove organics, nitrogenous compounds, phosphorous and antibiotic resistance bacteria, deep wetlands may represent a viable system for nutrient removal and tertiary treatment of sewage. Furthermore, these wetlands coupled with an appropriate pre-anaerobic unit can offer a compact and sustainable alternative for achieving high efficiency of removal of organics, nutrients, pathogens, and ARB from sewage, making it safe for reuse for irrigation.

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Customizing the Design of CWs Based on Treatment Standards

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Despite being an eco-friendly and sustainable technique, the large land requirement is the main factor that limits the use of constructed wetlands (CWs) as compared to other conventional treatment systems. To overcome this limitation, some researchers have suggested increasing the depth of the system without increasing the footprint or the stack design of different stages to reduce the footprint (Rampuria et al., 2020). Generally, vertical flow (VF) CWs require an area of 3–4 m^2 per population equivalent (p.e.) in cold regions and 1–2 m^2 per p.e. in warm regions (CPCB, 2019), while other conventional treatment systems such as activated sludge and trickling filter are sized at 0.2–0.4 and 0.3–0.7 m^2 per p.e., respectively for the removal of organics and TSS (Zapater-Pereyra et al., 2015). However, as per (Babatunde et al., 2008), this area is not sufficient for the removal of nutrients in CWs, and large area requirement was suggested that varies from 15 to 30 and 40–70 m^2 per p.e., for the removal of nitrogen and phosphorus, respectively. Therefore, CW treatment technology may be a cost-effective option, only where land is abundant and available at low cost (Zhai et al., 2011) unless design optimizations are carried out to minimize the area requirement.

Design of constructed wetlands

The k values along with the influent characteristics and effluent standards are routinely used for the calculation of one of the critical CW design parameters i.e. area of the CW. Assuming ideal plug flow characteristics and first-order reactions, the area required for the wetland can be calculated using the Kikuth equation (Kadlec and Wallace, 2009)

$$A = \frac{Q}{k_A} * \ln \frac{C_{in}}{C_{out}} \qquad (1)$$

Where k_A denotes the areal removal rate coefficient in md^{-1}, Q is the flow in m^3d^{-1}, A is the area of the wetland and C_{in} and C_{out} are the concentration at the inlet and outlet in mgL^{-1}. The outlet concentration of the pollutant may be substituted as per the prevailing standards in the region. During the calculations, the k_A values are derived from the literature (Kadlec and Wallace, 2009). Although these literature derived values are based on input output data of experimental wetlands (62 VFCW as given in Kadlec and Wallace, 2009), large deviations are observed from the mean values. For example, 0.05 and 0.95 percentile of VFCW k values have been reported as 19 and 1694 myr^{-1} or 0.052 and 4.64 md^{-1} (Kadlec and Wallace, 2009). Our recent work has shown that the k values derived from existing VFCW can be highly variable (Soti et al., 2022) and therefore the corresponding mean values may not be representative of the VFCWs operating under different conditions. This uncertainty culminates in the overdesign of the systems, which is undesirable as the large land requirement is a common constraint, especially in dense cities, that limits the usage of CWs in urban settings compared to other conventional treatment technologies (Zapater-Pereyra et al., 2015).

Deriving realistic k values by logical data classification in VFCWs

The area calculations for CW design are commonly carried out following Kikuth approach where the removal rate constant (K) is derived from literature. Our investigation on secondary data of 82 vertical flow CWs, yielded wide variations (0.0003 – 0.822 md^{-1}) in the calculated K values for different pollutants under different environmental and operational conditions indicating that it is important to incorporate the desired levels of pollutant removal to arrive at customized design of CWs. The results indicated that the relative standard deviation of K values could be narrowed by classifying the datasets based on design parameters like depth, hydraulic loading rates and substrate loading rates (Soti et al. 2022, Fig 1).

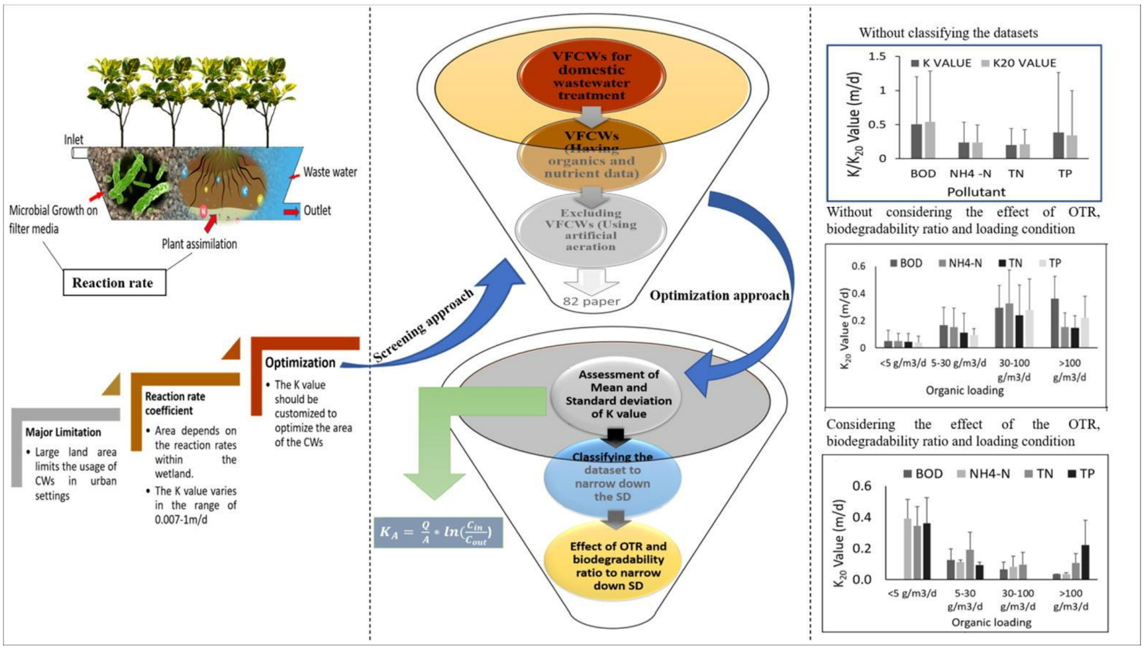

Fig 1. Reduction in the standard deviation in observed k values by logical classification of datasets (Soti et al., 2022)

These calculations can help arrive at more scientific design of CW to achieve the prevailing standards for the discharge or reuse of sewage.

Deriving realistic k values by logical data classification in HFCWs

The other most commonly used approach for calculating CW area in subsurface flow constructed wetlands is the P-k-C* first-order model. The area calculation in P-k-C*approach depends upon the areal removal rate constant (k), background concentrations (C*) and non-idealized hydraulics in steady state conditions (Ventura et al., 2022).

$$A = \frac{PQ_i}{K}\left[\left(\frac{C_i - C_*}{C_o - C_*}\right)^{\frac{1}{P}} - \mathbf{1}\right]$$

Where, C_o = outlet concentration, mg/l, C_i = inlet concentration, mg/l, C_* = background concentration, mg/l, K = first-order areal rate coefficient, m/d, P = apparent number of tanks in series (TIS), dimensionless, Q_i = influent flow rate, m³/d.

Secondary data of 74 HFCWs were used to calculate the k values using the reverse P-k-C* approach (Singh et al., 2022). The relative standard deviations were minimized by classifying the datasets based on organic loading rate, temperature and depth. Following the elimination of CWs with low organic loading rates and high biodegradability ratio (COD/BOD>3), the standard deviation was reduced up to 4.85% in the case of organic loading, 3.44% in case of temperature and 6.89% in case of depth. Area calculation using customized k values (Fig 2) would help to avoid unnecessary provision of the excessive land area commonly found in field CWs. It will also aid in identifying the nutrient governing area requirement and designing the CW accordingly.

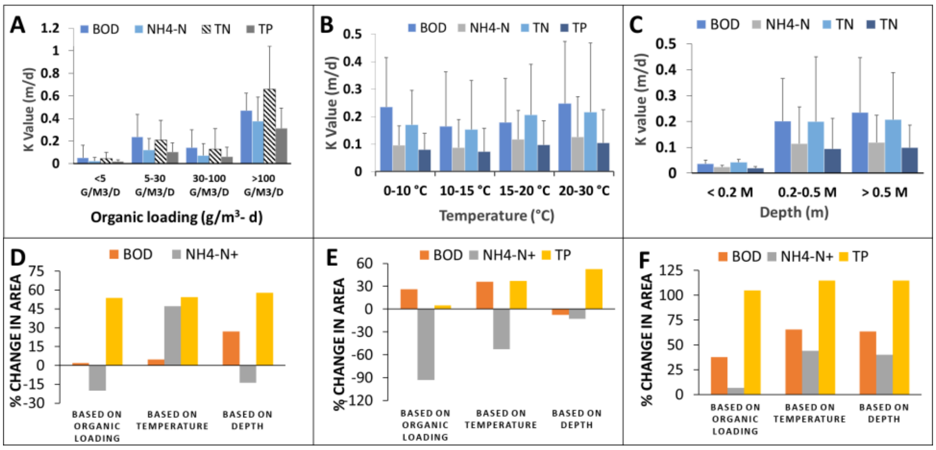

Fig 2. Reduction in standard deviation (A,B,C) and decrease in area (D,E,F) calculated using p-K-C* approach in HFCWs (Singh et al., 2022)

Deriving k values for nutrient removal in low OLR CWs

The complex, non-linear behaviour of the biological reactions due to inter-reliant physical, chemical, and biological parameters makes the design guidelines for CWs treating low organics wastewater a very challenging task. Machine learning (ML) techniques are best suited to solve complex problems and they also provide a better relationship (non-linear) to learn the datasets and build the model between input and output parameters. Different machine leaning approaches have been utilized to derive realistic k values for nutrient removal in low organic loading systems. Secondary datasets of 42 low organic loading Vertical flow constructed wetlands were assessed to optimize their area requirements for N and P (nutrients) removal. Significant variations in removal rate coefficients (k20) (0.002–0.464 m d−1) indicated scope for optimization. Data classification based on nitrogen loading rate, temperature and depth could reduce the relative standard deviations of the k20 values only in some cases. As an alternative method of deriving k20 values, the effluent concentrations of the targeted pollutants were predicted using two machine learning approaches, MLR and SVR (Fig 3). The latter was found to perform better (R^2 =0.87-0.9; RMSE = 0.08-3.64) as validated using primary data of a lab-scale VFCW. The generated model equations for predicting effluent parameters and computing corresponding k20 values can assist in a customized design for nutrient removal employing minimal surface area for such systems for attaining the desired standards.

Our previous work on secondary data of 74 horizontal flow constructed wetlands (HFCWs) demonstrated that large variation in areal removal rate constant (k) values could be reduced by classification and elimination of datasets with low-OLR and biodegradability ratios. This strategy was effective for prediction of k values for high-OLR wetlands, but was ineffective for low-OLR wetlands, likely due to differences in microflora as revealed by metagenomic analysis. To derive realistic k values for HFCWs, the remaining 37 low-OLR HFCWs (n = 544) were assessed in detail to derive a suitable approach for computing case-specific k values. The initial huge fluctuations in k values (SD, 83.41%) were reduced up to 39.2 % by classifying the datasets. A machine learning strategy employing SVR, RF, and ANN was tested and the best prediction efficiency on unseen datasets was achieved through ANN model with $R^2(k_{TKN})$ = 0.768 (RMSE 0.067); $R^2(k_{TN})$ = 0.835 (RMSE 0.043); and $R^2(k_{TP})$ = 0.723 (RMSE 0.087) (Table 1). The outcome was validated using primary data of HFCW which also corroborated the superiority of ANN based model for k value prediction. The ANN model generated in this work can be used for design customization of low-OLR HFCWs for optimizing the area required for removal of different nutrients.

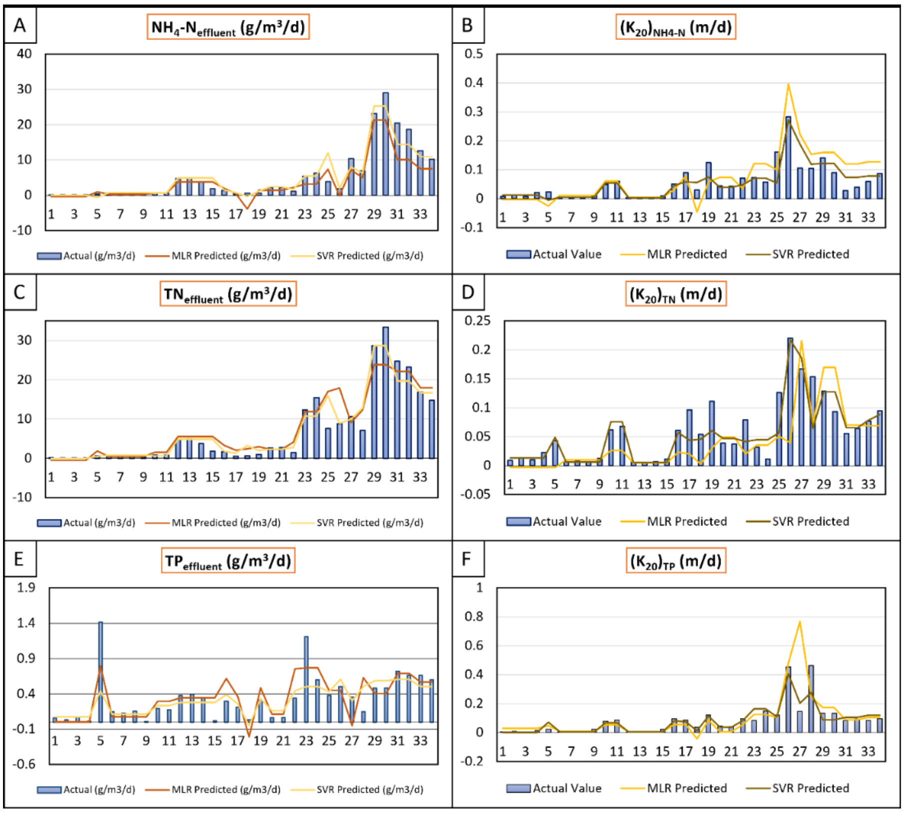

Fig 3. Comparison between actual and predicted effluent (A) and actual and predicted k_{20} values through MLR and SVR approach by using the effluent concentration in (g/m^3d^{-1}) (Soti et al., 2023)

Table 1. Comparison between RMSE and SDs of k values **(Singh et al., 2023)**

Prediction output	**P-k-C* Approach**		**SVR on unseen datasets**		**RF on unseen datasets**		**ANN on unseen datasets**	
	R^2	**SDs**	**R^2**	**RMSE**	**R^2**	**RMSE**	**R^2**	**RMSE**
k_{TKN}	0.657	33.80%	0.512	9.70%	0.635	8.70%	0.768	6.7%
k_{TN}	0.711	36.95%	0.600	8.50%	0.701	6.20%	0.835	4.3%
k_{TP}	0.637	34.86%	0.429	16.50%	0.596	13.10%	0.723	8.7%

Depth optimization in HFCWs using Machine learning

Varying the depth of HFCW media causes differences in the redox status within the system affecting the removal rates of different pollutants and may be exploited for removal of specific pollutant(s). Secondary data of 111 HFCWs (1232 datasets) were analysed by us to deduce the relationship between volumetric removal rate coefficients (K_{BOD}, K_{TN}, K_{TKN}, and K_{TP}) and depth (Singh et al. 2023). The equations of media depth were derived in terms of rate coefficients using machine learning approach (MLR and SVR) (R^2=0.85,0.87, RMSE=2.78%, 4.12%, MSE=2.17%, 3.99%, respectively on testing datasets). These equations were then used to find the optimum depth for pollutant(s) removal using the Grey wolf optimization (GWO) (Fig 4). This led to predicted optimum depths of 1.48, 1.71, 1.91, 2.09, and 2.14 m for the removal of BOD, TKN, TN, TP, and combined nutrients, respectively. These values were validated using primary data. This study would be helpful as design guidelines for removal of specific pollutant(s) in HFCWs.

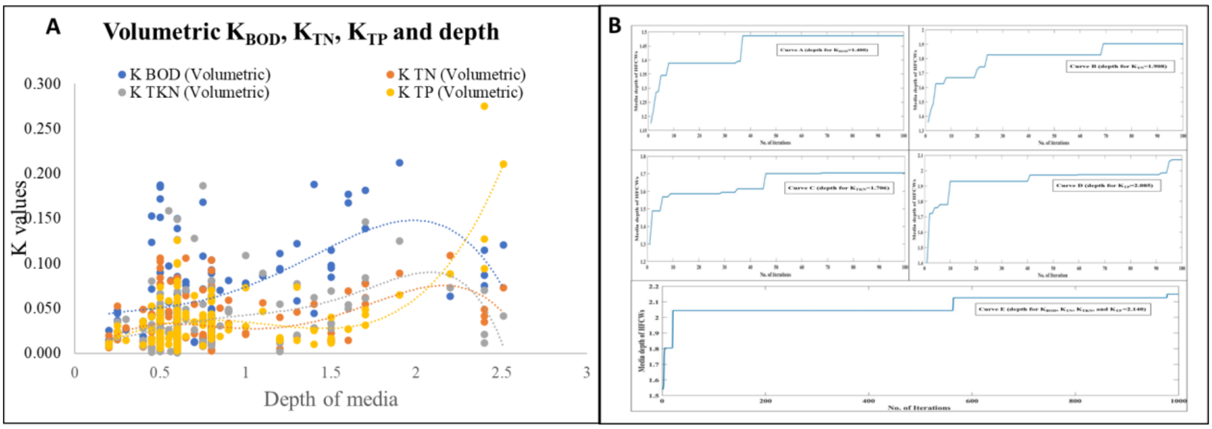

Fig 4. Correlation curve between depth of filler media and k values for different pollutants (A) and Greywolf optimization using MATLAB (B) (Singh et al., 2023)

A Stepwise approach for reducing land footprint

CWs offer an environment friendly solution, but their economic viability can be limited by land availability and the associated costs. To address this challenge, a systematic and step-by-step approach, was adopted to minimize the land footprint, compared to the specified Central Pollution Control Board (CPCB) standards of 3-5 m^2 per Population Equivalent (PE) (CPCB 2019). The population equivalent (PE) was calculated based on the relation 1 PE = 60 g BOD d^{-1} (Ilyas and Masih, 2017).

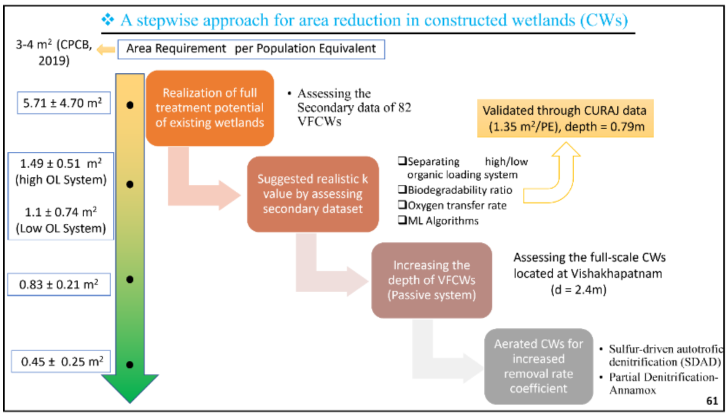

Fig 5. A stepwise approach for area reduction in CWs (Soti, 2024)

Upon evaluating the secondary dataset of full-scale VFCWs, the land footprint was determined to be 5.71 ± 4.70 m^2 per PE. The huge variation in land footprint was reduced considerably through a systematic classification of the dataset into high and low organic loading systems. Following this approach, the land footprint in high organic loading systems was significantly reduced to 1.49 ± 0.51 m^2 per PE and in low organic loading systems, it was reduced to 1.1 ± 0.74 m^2 per PE. This reduction was achieved through the application of the optimized k values, which were validated through primary data from full scale VFCW located at CURAJ. This VFCW shares similar depth characteristics and has an area of approximately 1.35 m^2 per PE.
Furthermore, incorporation of the depth factor in passive VFCWs led to a further decrease in land footprint, reaching a value of 0.83 ± 0.21 m^2 per PE. The introduction of artificial aeration played a transformative role, reducing the land footprint to 0.45 ± 0.25 m^2 per PE, which is approximately 1/10th of the area stipulated by CPCB standards (3 to 5 m^2 per PE). Thus, a strategic optimization of key parameters, including the k value, depth, and aeration, played a crucial role in significantly reducing the land requirements for CWs, making them a competitive wastewater treatment technology with land area requirements similar to Activated sludge process (0.2-0.4 m^2 per PE) and Trickling filter process (0.3-0.7 m^2 per PE) (CPCB Manual, 2004).

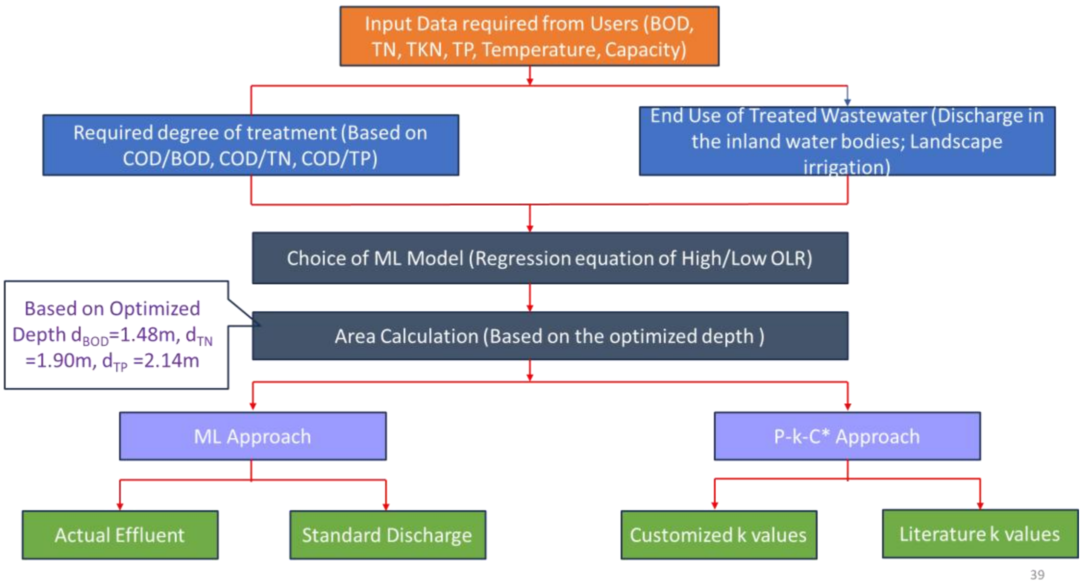

Fig 6: Framework for the customized design for optimal operation of CWs (Singh, 2024)

Following these observations and results, a conceptual framework was developed for the design of the VFCW (Fig 6), wherein the user can input data like influent wastewater parameters, required degree of treatment and the intended end-use of the treated wastewater. The model equations developed for predicting the effluent parameters can then be used for computing the corresponding optimized k_{20} values, and the respective area requirements in a case-specific manner. This system would offer a tailored design of CWs for organics and nutrient removal. The use of this framework will ensure minimal surface area requirement while meeting the desired standards, thus demonstrating the potential of CWs in optimizing land use for sustainable and effective wastewater treatment.

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Energy Efficient Wastewater Treatment Systems (L)

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Introduction

Anaerobic treatment of domestic wastewater is not a new concept and from time immemorial septic tanks, soak pits, cesspool, etc. have been used. Since these systems can only partially treat the sewage and, the effluent still contains high concentration of organic matter, suspended solids and nutrients, the interest for sewage treatment switched over to aerobic treatment systems. There are numerous aerobic treatment systems some of which include, activated sludge process (ASP), fluidized bed reactors (FBR), trickling filter (TF), aerated lagoons and oxidation ponds. Regardless of the good treatment performance and low land requirement of aerobic systems; these methods suffer from plentiful drawbacks as compared to anaerobic treatment systems (also summarized in Table 1) (Lettinga, 2008):

- Energy intensive;
- Production of high and poorly stabilized sludge (60–70% of incoming COD is converted to biomass);
- High investment and operational/maintenance cost;
- Complex infrastructure.

Though, most of the above mentioned drawbacks are not associated with oxidation ponds but high land area is needed which is very uneconomical in densely populated countries like India. Therefore, these mentioned drawbacks make the anaerobic systems suitable for rural areas and developing countries. With the advent of high rate anaerobic systems such as up-flow anaerobic sludge blanket reactor (UASB), anaerobic contact process, anaerobic filter (AF) or fixed film reactors and fluidized bed reactors, which promote a good contact between the inflow wastewater and the micro-organisms at high concentration and consequently high organic matter removal at short retention times, the strategy for the treatment of sewage was shifted back to anaerobic process which has the advantages of low cost, energy recovery in the form of biogas, operational simplicity, low energy consumption, and low production of digested sludge. In 1970s, due to the energy crisis and relatively less expensive treatment concept, the UASB process was recognized as one of the most feasible method for the treatment of sewage in developing tropical and sub-tropical countries like India, Brazil and Colombia where financial resources are generally scarce. Since 1980, the discussion on the applicability of UASB process for the treatment of sewage has been presented by Lettinga and co-researchers (Lettinga et al., 1980, 1981, 1993; Lettinga and Hulshoff Pol, 1986; Seghezzo et al., 2002; von Sperling and Chernicharo, 2005; Lettinga, 2008) and the results indicated that about 70% chemical oxygen demand (COD) removal can be achieved in warm climates countries (Schellinkhout et al., 1985; Souza, 1986; Siddiqi, 1990; Khan, 2011). Presently about 30 UASB based STPs were installed in India since late 1980s and more than 20 are under construction (MoEF, 2005 and 2006). Therefore, single step UASB process undoubtedly experienced as an attractive option in warm climate regions.

However, the treatment efficiency decreases with the decrease in temperature, reaching a 50% COD removal at 15°C (Elmitwalli et al., 2001; Singh and Viraraghavan, 2002; Lew et al., 2003). The UASB reactor performance at low temperatures can be improved by changing its configuration like incorporating settler above the GLSS (gas–liquid–solid separator), or adding the AF at the top of the UASB reactor, making it as a high rate anaerobic hybrid reactor and extended (staged) types of UASB-systems, viz. UASB-reactors completed with an AF or supplemented with additional sludge digester operated at optimal temperature for stabilizing sludge ‘extracted’ from the UASB reactor, which following its stabilization in the digester partially will be return to the UASB reactor in order to keep the methanogenic activity at a sufficiently high level. The performance of UASB-Digester system for organic matter removal was observed substantially better at temperature of 15°C as compared to single step UASB reactor at low temperature (Mahmoud, 2002). The two-step UASB system was studied by various authors (Sayed and Fergala, 1995; Halalsheh, 2002; Seghezzo, 2004). However, results showed similar performance of the two-step reactor in comparison to a one-step system, due to lower removal efficiencies in the second stage, which was attributed to low sludge retention time (SRT). Typical problems of highly loaded UASB reactors like sludge flotation and washout of active biomass were observed, mainly at temperatures below 20 ◦C. Wang (1994) evaluated a two stage system composed of UASB-EGSB (expanded granular sludge bed) for sewage treatment at low temperature. The primary objective of the first-step treatment was the removal and partial hydrolysis of suspended COD and the second-step process observed to convert the dissolved COD to energy rich methane gas.

Further, due to growing concern over the impact of sewage contamination of rivers and lakes and increasing scarcity of water in the world along with rapid population increase in urban areas gives reason to consider appropriate technologies for sewage treatment so that sewage can be treated up to reuse standard. The anaerobic processes constitute the core method in the natural biological mineralization (NBM) treatment concept for treatment of low and high strength wastewaters. High rate anaerobic treatment systems, such as UASB process combined with the complementary NBM system, definitely represent a possible route to sustainable environmental protection in spirit even towards a more sustainable society. Still researchers realized great challenging improvements in NBM route/field in order to get sufficient confidence among policy/decision makers, engineers, etc. The maximum reuse/or recovery of resources can be achieved through anaerobic pre-treatment (UASB) followed by the treatment concepts applied based on the natural biological mineralization sequence/or route (NBMS). Moreover, at the same time less energy consumption can be realized in comparison with purely aerobic treatment systems. Thus by far, the UASB process has been demonstrated as a robust technology for sewage treatment, mainly for developing countries and/or small communities (Lettinga et al., 1980, 1993; Hulshoff and Lettinga, 1986; van Haandel and Lettinga, 1994; Verstraete and Vandevivere, 1999; Arceivala, 2001; Gnanadipathy and Polprasert, 1993; Sousa and Foresti, 1996; Foresti, 2001; Chernicharo, 2006; Schellinkhout and Collazos, 1992; Seghezzo et al., 1998; von Sperling and Chernicharo, 2005; Tandukar et al., 2006a,b). Moreover, the UASB reactor treating domestic wastewater can produce two main resources, which can be recovered and utilized: methane and the effluent. The valuable byproduct methane produced during COD removal can be recovered (from 28% to 75%) and transformed into energy (Mendoza et al., 2009). In energy terms, 1 m^3 of biogas with 75% methane content is equivalent to 1.4 kW-h electricity. The biogas can be used to run dual fuel generators or street lighting (Arceivala and Asolkar, 2007).

In spite of well proven advantages, the effluent of UASB reactor does not comply with the effluent discharge standards established by various environmental agencies (Chernicharo, 2006; Tandukar et al., 2006a,b). The effluent of UASB reactor treating sewage contains high nutrient and pathogens including sufficiently high amount of residual organic matter. The treated effluent for reuse must meet certain controls such as pathogens concentrations follow the WHO (1989) standards. To prevent the pollution of receiving water bodies and make it up to reuse standards, stringent discharge legislations must be required. To develop a national effluent standard, it is necessary to consider a variety of local geographical, socio-economic, dietary and industrial conditions (WHO, 1989). The national standards therefore, differ appreciably from the WHO guideline values as well as between different countries. For example, effluent discharge standards in Israel are more stringent than in India: standards guidelines for TSS in Israel are 10 mg/L whereas in India the values are 100 mg/L for discharge into water bodies. Moreover, the Flemish standards for effluent discharge (for domestic wastewater) into surface water bodies, which follows the European Union environmental legislations is more/less stringent than the Israeli standard, (BOD = 25 mg/L; TSS = 35 mg/L). Despite the differences in guideline, these values are hardly achieved through single anaerobic processes. Thus, UASB reactor alone renders an effluent which is not suitable for agriculture re-use and/or discharge into water bodies. However, it can be used as a first step in wastewater treatment mainly for organic matter removal especially in regions where financial resources are scarce. To protect the receiving water bodies and to reuse treated water for restricted as well as unrestricted irrigation, it is necessary to further treat effluent from UASB reactor, i.e. a post-treatment system. The main role of the UASB post-treatment systems is to attain the effluent disposal guidelines with a complete removal of organic matter; as well as removal of constituents little affected by the anaerobic treatment, such as nutrients; reduced inorganic (sulfide, ferrous, etc.) compounds, and pathogenic organisms (viruses, bacteria, protozoa and helminthes) along with resources recovery, and/or valorization of mineralized compounds. The complete removal of organic pollutants could be possible if the sewage can be treated via a sequential anaerobic, microaerobic and fully aerobic biodegradation of the pollutants on the basis of processes proceeding according to the biological C–N and S-cycle, together with associated chemical and physical processes. This treatment concept enables conserving/or recovery of useful byproducts in the form of fertilizers, soil conditioners and renewable energy.

The full-length article on "Sustainable options of post treatment of UASB effluent treating sewage: A review" can be found on https://doi.org/10.1016/j.resconrec.2011.05.017

Constructed Wetlands for Village Ponds

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Introduction

Wastewater is water that has been used and must be treated before it is released into another body of water, so that it does not cause further pollution of water sources. Wastewater comes from a variety of sources. Water that has been used, as for washing, flushing, or in a manufacturing process, and so contains waste products; sewage. Sewage is the subset of wastewater that is contaminated with faeces or urine, but is often used to mean any wastewater. Sewage includes domestic, municipal, or industrial liquid waste products disposed of, usually via a pipe or sewer (sanitary or combined). Sewerage is the physical infrastructure, including pipes, pumps, screens, channels etc. used to convey sewage from its origin to the point of eventual treatment or disposal. It is found in all types of sewage treatment, with the exception of septic systems, which treat sewage on-site. The environment and the human health are closely interrelated. The well-being of the people is the reflection of the healthy environment, but both can damage by pollution. Pollutants released into air, water and soil can find their way in to human body by breathing, eating and drinking. Growing urbanization, rapid industrialization without proper plan, excess use of chemical fertilizers, insecticides, pesticides in agriculture field has deteriorated the quality of water, causing water pollution. In broad perspective “Pollution” means such contamination of water or such alteration of the physical, chemical or biological properties of water or such discharge of any sewage or trade effluent or of any other liquid, gaseous or solid substance into water (whether directly or indirectly) as may, or is likely to, create a nuisance or render such water harmful or injurious to public health or safety, or to domestic, commercial, industrial, agricultural or other legitimate uses, or to the life and health of animals or plants or of aquatic organisms (Govt. of India, 1974).

Villages in sub-tropical countries are facing stagnation of drains and choked ponds, which are in dire need of renovation so that the ponds can be effectively utilized as a source of water for agriculture, aquaculture and potentially even bathing and drinking. Village ponds can also reduce flood impacts during monsoon seasons and facilitate ground water recharge, enhancing the availability of water throughout the year. Village ponds also support biodiversity, cultural services, and carbon sequestration. Currently, however, many village ponds in these regions are filled with domestic wastewater and solid waste. Disposal of wastewater in village ponds is a major public health concern as the stagnant water smells bad and leads to the spread of many diseases. Pond is referred to as man-made or natural water body which holds water for four months of the year or more and normally used as the groundwater recharge source (Mushtaq et al., 2006; Passy et al., 2012; Rajaram & Das, 2008).Now a days, pond water is becoming polluted mainly due to discharge of wastewater from houses and septic tanks as rural area are not having any sewage treatment plant (Joshi et al., 2013; Reddy & Behera, 2006; Shellenbarger et al., 2008). Since, ponds are playing important role in groundwater recharge so pond water quality needs to be ascertained by strategic management of these resources (Shirodkar et al., 2009; Sood et al., 2008; Srinivasan & Reddy, 2009; Wang et al., 2010).

In rural areas, ponds used to be lifeline for the villagers as rain water and runoff water stored in ponds was commonly used for the irrigation, drinking & bathing purposes of domestic animals, etc.. However, nowadays wastewater from households, septic tanks is also finding its way into the village ponds (Green & Ward, 2011; Hong et al., 2010; Inoue et al., 2009; Islam et al., 2011; Jurzik et al., 2010). Further, it may also be observed that people uses surrounding of ponds for dumping of house hold solid wastes, cattle dung, storing cattle dung cake as animal habitat and for open defecation. Therefore, there are probable chances of contamination of pond water. These ponds are unlined, therefore water present in the ponds keep on percolating through subsoil and subsequently pollutants of ponds likely to contaminate ground water at shallow depths.

Therefore, natural treatment system considered to be the most cost effective and environmental friendly method to reduce the contaminants before discharge into the ponds. Natural treatment systems for wastewater (NTS) have been shown to be suitable for application in urban and rural environments (Mendieta-Pino et al., 2021). NTS have a low energy cost, a high capacity for the elimination of contaminants, and allow an adequate reuse of the effluent. Therefore, NTS technology has been used to treat the wastewater for the conservation of village ponds. In the present study, two type of natural treatment system installed in the study area i.e. Ibrahimpur Masahi, Muzaffarnagar and Baghpat to see the efficiency of these treatment system to reduce the contaminants in wastewater.

Review of the Literature

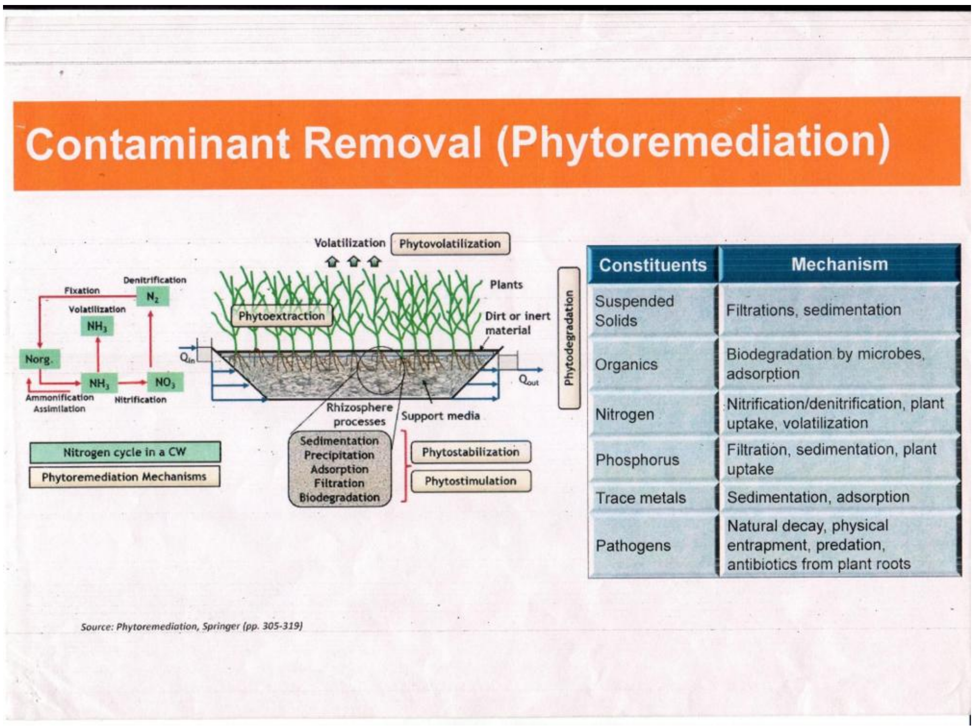
'Phytoremediation' word is a combination of two different words in which the first word is taken from the Greek word 'Phyto' means plant, and the second word is the Latin word 'remedium' means to reduce or remove an evil (Cunningham et al., 1996). Phytoremediation is defined as the use of plants and their associated micro-organisms for the reduction of contaminants in wastewater and contaminated soil. Phytoremediation technique is also called “Green remediation” and “Botanical bioremediation”. This plant-based wastewater treatment technology has widely been used for the enhancement of environmental clean-up by removing pollutants and heavy metals present in wastewater (Pilon-Smiths, 2005; Cook and Hesterberg, 2013). The mechanized or conventional treatment technologies require high financial cost, energy, and skilled labor for the treatment of wastewater. The phytoremediation technology is used as an alternative or complimentary for wastewater treatment. It is an in-situ wastewater treatment/remediation technology in which living plants are used to reduce pollutants for removing contamination. It is also an eco-friendly, solar-energy-driven clean-up technology because solar radiation is used by plants for the photosynthesis process and uses nutrients. It is based on the concept of nature to cleanse nature.

In the 1950s, German Scientist Kathe Siedel made the first constructed wetland (CWs) for wastewater treatment. In the late 1960s, the first full-scale CW was made and at present in Europe, more than 50,000 and in North America more than 10,000 CWs are operating for wastewater treatment (Kadlec and Wallace 2009; Vymazal, 2011; Yan and Xu, 2014). In developing countries, especially in China, thousands of CWs are used as an alternative technique for wastewater treatment (Chen et al. 2011). In the 1960s and 1970s, mainly domestic and municipal wastewater were treated using CWs. However, in recent years, CWs are used for the treatment of a variety of wastewaters like domestic wastewater, industrial effluents, agricultural effluents, mine drains, leachates, polluted ponds, rivers, lakes, highway runoff, etc. for different climatic conditions (Wu et al., 2014). Many types of pollutants can be removed by plants like heavy metals, agricultural pesticides, explosives, and petroleum oil (USEPA, 2000). In tropical areas, the potential use of this phytoremediation technology is high due to the favorable climatic conditions which enhance plant growth and stimulates microbial activity (Zhang *et al.,* 2010). In recent times, the industrial economy and excessive use of chemicals used in agriculture (pesticides, herbicides, and fertilizers) result in environmental degradation around the world, so scientists and researchers are busy developing new techniques for solving this problem and removing contaminants from wastewater. The phytoremediation technique is one of them (USEPA, 2000).

The working mechanisms and performance efficiency of any phytoremediation technology mainly depend on the type of contaminants (strong, medium, and weak), bio-availability, and soil properties (texture and structure) (Cunningham and Ow, 1996). In phytoremediation technology, there are several ways by which plants can remedy and remove contaminants on site. The plant uptake contaminants by the root system, which is the main mechanism for reducing toxicity. For plant growth, the plant’s root provides a large area that accumulates contaminants and nutrients (Raskin and Ensley, 2000). The presence of bacteria and other microorganisms in the soil rhizosphere is 100 times larger than in soil outside the rhizosphere (USEPA, 2000), which helps in breaking down the contaminants.

According to Garbisu (2002), phytoremediation is a cost-effective, non-intrusive, and aesthetically pleasing technique in which some specific plant species are used to remove or reduce various contaminants present in the wastewater by plant tissues. The phytoremediation technology is widely used for the removal of contaminants such as radionuclides, metals (heavy and toxic), organic compounds like poly chloro-bi-phenyls, polycyclic aromatic hydrocarbons, chlorinated solvents, insecticides, pesticides, explosives, and surfactants. Macek (2004), used green plants and microbes as a bioremediation technique to reduce the harmful pollutants like recalcitrant organic compounds or heavy metals in wastewater. Some specific plant species were used for bioremediation as plants reduce the contaminants and prevent the leaching of toxic substances to the surrounding areas. According to Huang and Cunningham (1996), by using genetic engineering, it is possible to modify plant characteristics in such a way that plants can remove contaminants easily, fast, and significantly from the wastewater.

Mechanism of Contaminant Removal under Natural Treatment Systems



Study Area

Ponds from the identified villages of Dist. Haridwar (Ibrahimpur Masahi, Teh: Bhagwanpur, Fig. 1a), Dist. Muzaffarnagar, Meerut and Baghpat in western Uttar Pradesh (Fig. 1b) were selected for the study. The study area is located in the Doab region of Indo-Gangetic Plain, with monsoon influenced humid subtropical climate. The study area (i.e. Ibrahimpur Masahi revenue village) is falling under the Shipla Nadi-Halzora Nadi watershed, District Haridwar (Uttarakhand).

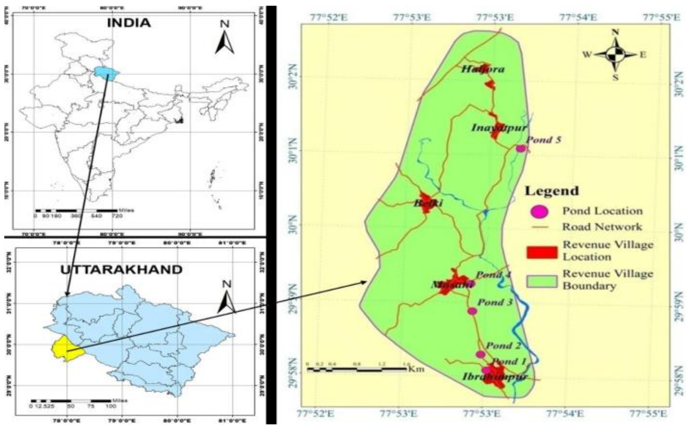


Fig. 1a: Study area of ponds located in Ibrahimpur Masahi, Haridwar(Uttarakhand)

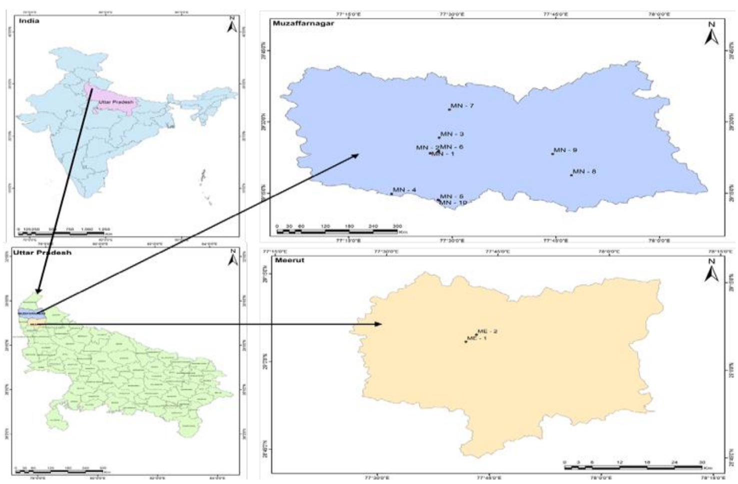


Fig. 1b: Study area of ponds located in Muzaffarnagar, Meerut and Baghpat Dist. (U.P.)

On Site Remediation of Rural Wastewater in a Village Ibrahimpur Masahi (Dist. Haridwar, Uttarakhand): A Constructed Wetland based Natural Treatment System

The ponds are generally used as sink for all wastewater as well as for solid waste generated in the villages. Accordingly, village ponds are going to vanish due to the entry of sewage causing eutrophication. Therefore, it is proposed to rejuvenate pond (s) through establishment of a CW based Natural Treatment System (NTS) for treating village wastewater entering in the ponds and developing ponds for increasing rainwater harvesting potential for the benefit of local peoples. The Ibrahimpur Masahi Revenue Village (Dist. Haridwar) has five ponds which receive seasonal storm water and daily sewage and sullage of the designated sub-village communities. During the past few years, there is heavy deposition of silts and wastewater taken place which resulted in eutrophication. Also, the collected wastewater routinely pumped to the agricultural field and the natural functioning of all the ponds is completely got away. Currently, none of the pond is suitable for fishery, however, can be rejuvenating and may be fit for fishery and aquaculture activities. The essential activities for rejuvenation may involve the retrofitting of existing pond through implementation of natural treatment system for treatment of upcoming wastewater and the resulted treated wastewater may be used as balance water for fish pond. Following scheme may be implementing for rejuvenation of village ponds (Fig. 2a).

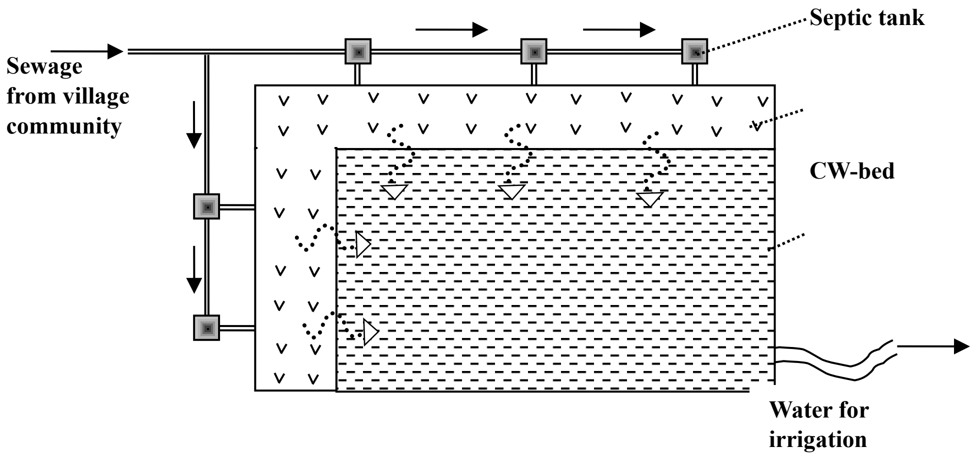


Fig. 2a. Typical scheme diagram for rejuvenation of village ponds (**Source:** Dinesh Kumar, Saroj Kumar Sharma and Shyam R. Asolekar, Chapter 10, Saph Pani Handbook-2016, an EU-funded Project (Eds. Wintgens, et al., 2016).

A brief details/Plan of a rejuvenated pond located in village Ibrahimpur Masahi (Dist. Haridwar) is shown as below (Fig. 2b & 2c). For effective evaluation of the CW-NTS, and assessment of its potential replicability in other village ponds, NIH has collaborated with UKCEH. The water quality of the rejuvenated pond in Ibrahimpur Village has been compared with a control pond (without any constructed wetland treatment) in a nearby village (Masahi Kala). Field investigations related to water quality, ecological quality, greenhouse gas emissions, groundwater quality and level, and social surveys of village attitudes to the constructed wetland and pond rejuvenation are carried out to jointly evaluate the benefits of the constructed wetland treatment solution.

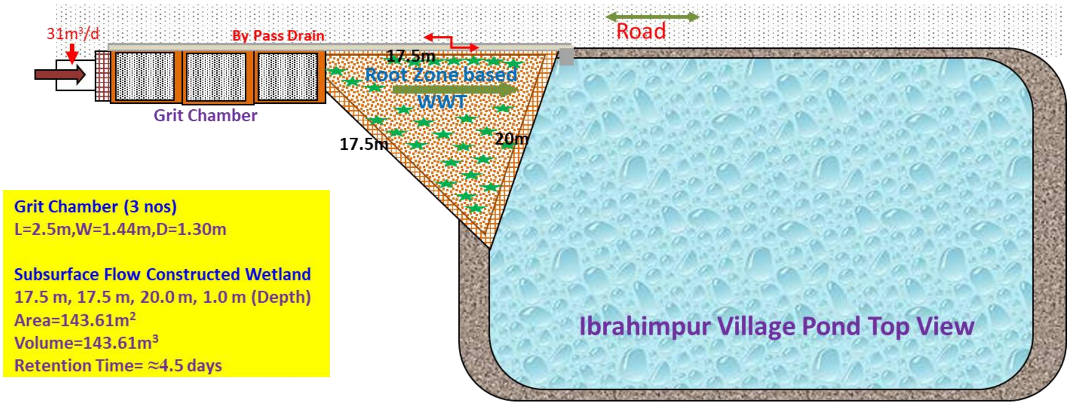


Fig. 2b: Plan of CW-NTS located in Village Ibrahimpur Masahi, Dist. Haridwar (Uttarakhand)


Fig.2c. A view pond rejuvenation in Ibrahimpur Masahi (Dis. Haridwar) by NIH

Rejuvenation of Identified ponds in Muzaffarnagar, Meerut and Baghpat Dist. (U.P.)

Almost on similar pattern, NIH has been entrusted a task to rejuvenate the identified ponds (22 nos.) of western U.P. in a retrofitting mode by carrying out de-weeding, de-silting, wastewater treatment and strengthening of the embankments. Also, it is proposed to establish an appropriate Natural Treatment System (NTS) technology, such as Floating Wetlands (FW), for treatment of the wastewater entering into these ponds. The rejuvenated ponds with treated wastewater shall then be used for groundwater recharge through rejuvenated pond, limited agricultural use, as well as for livelihood activities such as fishery. Initially, the degraded village pond was rejuvenated by de-weeding and desilting works. Thereafter, Natural treatment system i.e. constructed wetland and floating wetland was established in study area in order to evaluate the performance of NTS. Floating wetland technology for the treatment of wastewater entering into the ponds from village catchment area was installed in selected ponds. Construction of a sedimentation tank was considered a prerequisite for the installation of floating wetlands. Floating wetland treatment system was found to be working satisfactorily. Inlet chambers were constructed at all pond sites for filtering of solid waste at pond inlets. These chambers were constructed (Fig. 3) and are found working satisfactorily in filtering the incoming solid waste. Inlet channels in all ponds were cleaned and maintained for uninterrupted passage of incoming wastewater.

Fig. 3: Floating Wetland at Muzaffarnagar

Material and Methods

Sample Collection and Analysis

Pond water samples were collected from 15 to 20 cm below the surface in the month of June 2017. The samples were preserved and analysed for pH, EC, major ions, DO, BOD, COD, and Chlorophyll-a as per standard methods (APHA, 2012) in triplicates. Water temperature, pH, EC and DO were recorded onsite using SENSOREX AQUACHEM digital meter. DO in the water samples were also fixed in the field for analysis in the laboratory by Azide-Winkler titration method. COD of the samples was estimated using dichromate reflux titrimetric method. BOD was analysed using manometric respirometric method. Total phosphorus (TP) and total nitrogen (TN) were analysed.

Table 1: Parameters analysed in the laboratory

S. N.	Parameter	Method	Equipment Used
1	pH	Electrometric	pH meter
2	Electrical Conductivity	Electrometric	Conductivity meter
4	Nitrate	Conductivity Method	Ion Chromatograph
5	Ammonia		
6	Phosphate		
7	COD	$K_2Cr_2O_7$ digestion	Redox Titration
8	BOD	Respirometric	Oxitop BOD Analyzer
9	DO	ModifiedWinklerazide	Iodometric Titration

Monitoring of ground water level

The groundwater levels were monitored using different hand pumps located in the vicinity of the village pond. The details of monitored hand pumps and GW levels are given in Tables.

Table 2: Details of monitored hand pumps with GW Levels in Ibrahimpur Masahi

Hand Pump ID	Latitude	Longitude	Depth to Water (m, bgl)				
	N	E	Jan. 2017	Nov. 2017	Apr. 2018	Jun. 2019	Mar. 2020
HP01	29°58'21.47"	77°53'21.36"	-	13.6	13.8	14.4	12.5
HP02	29°58'26.30"	77°53'18.66"	-	14.2	14.4	14.8	13
HP03	29°58'23.69"	77°53'26.57"	14.3	14.5	14.7	15.3	13.6
HP04	29°58'17.38"	77°53'27.91"	-	17.6	17.9	17.7	-
HP05	29°58'22.70"	77°53'40.86"	3.5	3	3.1	-	2.4
HP06	29°58'29.40"	77°53'29.76"	9.43	7.54	7.73	8.3	6.62

Table 3: Groundwater level in identified villages of Muzaffarnagar			
	Location of Hand Pump	**GW Depth (BGL in m), June 2017**	**GW Depth (BGL in m) May-June (2019)**
Munnawarpur	Outside of village (0.5Km before Village)	9.7	9.99
	Entrance of village/Near Pond	7.94	8.33
	Middle of village	8.04	8.84
Antawara	Entrance of village/Near Pond	4.36	6.79
	Middle of village (I)	6.18	7.02
	Exit side	3.87	4.75
Shiwaya	Entrance of village/Near Pond	12.5	13.53
Pavli Khas	Entrance of village/Near Pond	13.51	14.13
	Pond/Near Pond	12.86	13.48
	Exit side/I km distance from pond	13.77	14.51
Roni Hazipur	Middle of village (I)	13.03	12.22
	Middle of village (II)	13.88	13.2
Mohamadpur Madan	Near Pond 2 HP	21.63	21.36
	Pond 1 Hand pump	21.2	20.79
Bhaura Khurd	Entrance of village	29.43	25.78
	HP Near pond1	28.31	25.94
	Hand pump near Pond 2	27.75	26.36
Biral	Entrance of village HP	37.27	33.52
	HP Near pond	33.7	33.8

Results and Discussions

To understand seasonal variation in water quality parameters of the wastewater entering the wetland, the wastewater samples were collected and analysed. The samples were collected almost always at the same time of day, around 11:00 HR. The samples were analysed for pH, electrical conductivity, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, nitrate-nitrogen, ammoniacal-nitrogen, phosphate.

pH & Electrical Conductivity

The pH value of domestic wastewater of Ibrahimpur was always higher than 7 and lower than 8.5(Fig. 4). The highest value of pH 8.35 was observed in February 2019 and the lowest value 7.0 was recorded in October 2019. The average annual pH value of the wastewater was 7.68±0.1. The electrical conductivity of the wastewater, an indicator of dissolved solids, ranged from 1280 µs/cm to 2178 µs/cm with an average value of 1820±72.42µs/cm (Fig.4). The lower values coincided with monsoon periods with rainwater diluting the minerals in the village wastewater(Basavarajappa & Manjunatha, 2015).

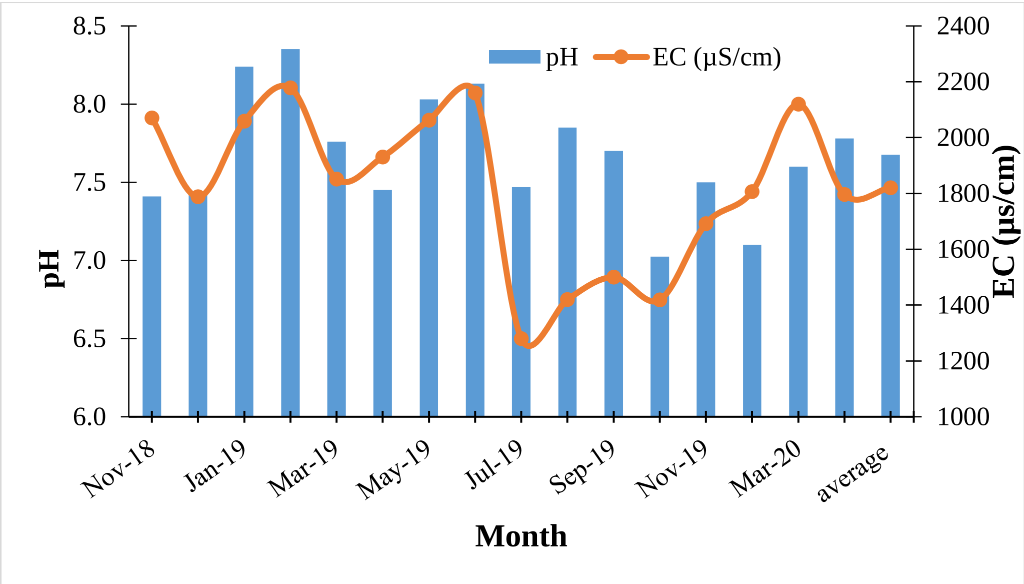


Fig.4: Monthly Variation in pH and Electrical Conductivity of Domestic Wastewater of Ibrahimpur Village

Dissolved Oxygen

The average annual dissolved oxygen (DO) of domestic wastewater was 0.64±0.8mg/L. The highest value of dissolved oxygen was recorded in May and June 2019 which were 1.2 mg/Land 1.1 mg/L respectively and the lowest value of dissolved oxygen was 0.2 mg/L in March and October 2020 (Fig. 5).

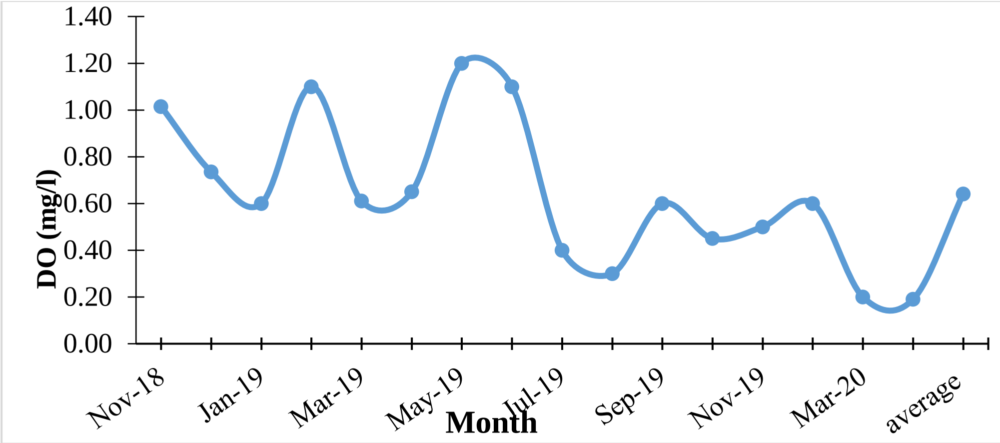


Fig.5: Monthly Variation in Dissolved Oxygen of Domestic Wastewater of Ibrahimpur Village

Biochemical Oxygen Demand& Chemical Oxygen Demand

The average value of Biochemical Oxygen Demand during the monitoring period was 245.31±71.63 mg/L. The maximum BOD value recorded was 360 mg/L in December 2018 and March 2019 and the minimum value, 130 mg/L, was recorded in November 2019. The COD values ranged from 250.36 mg/L in November 2019 to 739.16 mg/L in December 2018 with an average value of 505.82±36.99 mg/L (Fig. 6a). BOD variation in the water of Ibrahimpur Masahi pond (with constructed wetland) and Masahi Kala pond (no treatment) is given in Fig. 6b.

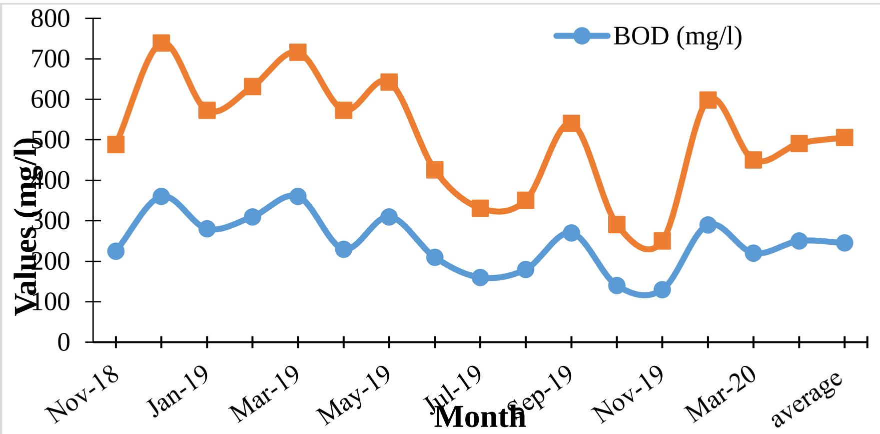


Fig. 6a: Monthly Variation of BOD and COD in Domestic Wastewater of Ibrahimpur Village

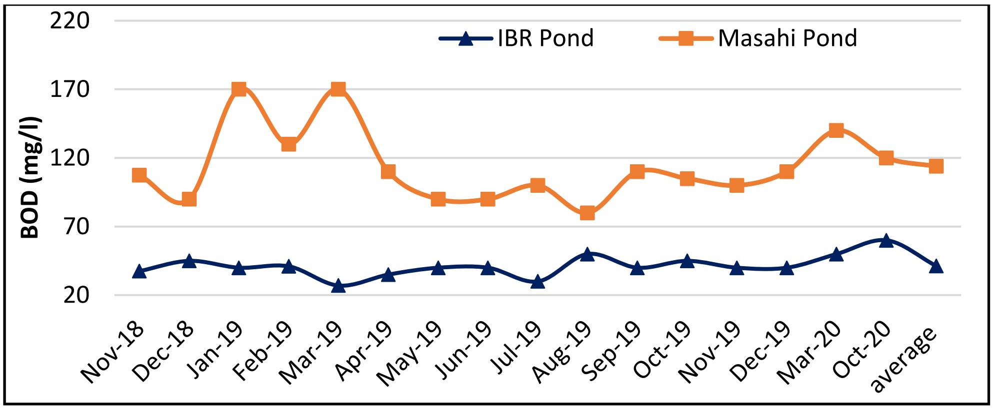


Fig. 6b. BOD variation in the water of Ibrahimpur Masahi pond (with constructed wetland) and Masahi Kala pond (no treatment).

Nitrate-Nitrogen, Ammoniacal-Nitrogen and Phosphate

Nitrate-nitrogen, Ammoniacal-nitrogen, and Phosphate in the wastewater samples were observed in the range 1.48 mg/L to 6.2 mg/L, 2.13 mg/L to 27.90 mg/L, and 1.2 mg/L to 6.59 mg/L, respectively (Fig. 7). The average concentration of NO_3-N, NH_4-N, and PO_4 was recorded 2.68±0.29 mg/L, 9.42±1.77mg/L, and 3.02±0.38 mg/L respectively.

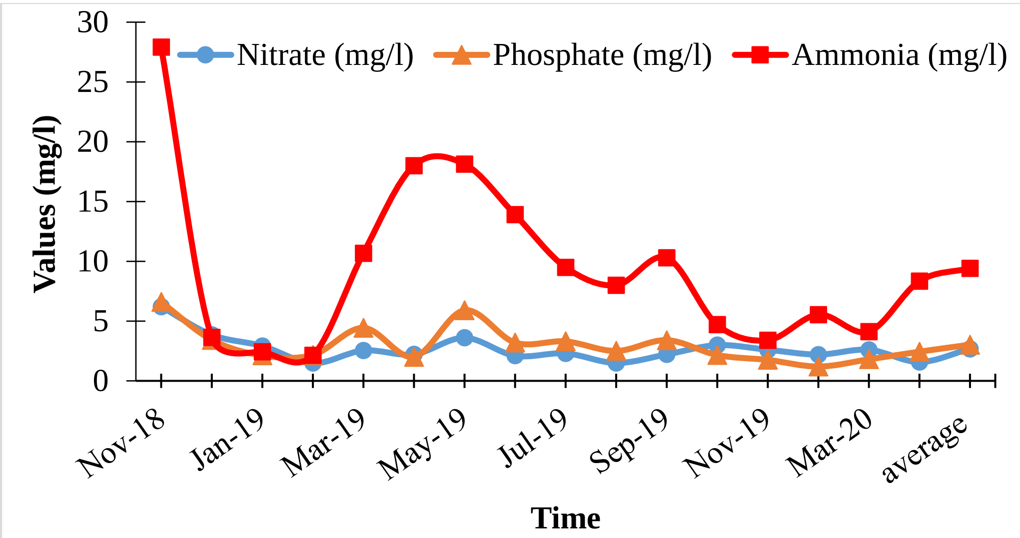


Fig. 7: Monthly Variation in NO_3-N, NH_4-N, and $PO_4$of Domestic Wastewater of Ibrahimpur Village

Bacteriological analysis

Coliforms in the water are used as a proxy indicator of pathogenic bacteria and therefore were analyzed in the wastewater and the treatment chain. The total coliforms and *E.coli* in the wastewater were observed in the range $2.04 x 10^6$ MPN/100 mL to $7.7 x 10^8$ MPN/100 mL and $2.6 x 10^5$ MPN/100 mL to $4.61 x 10^7$ MPN/100 mL respectively (Fig. 8).

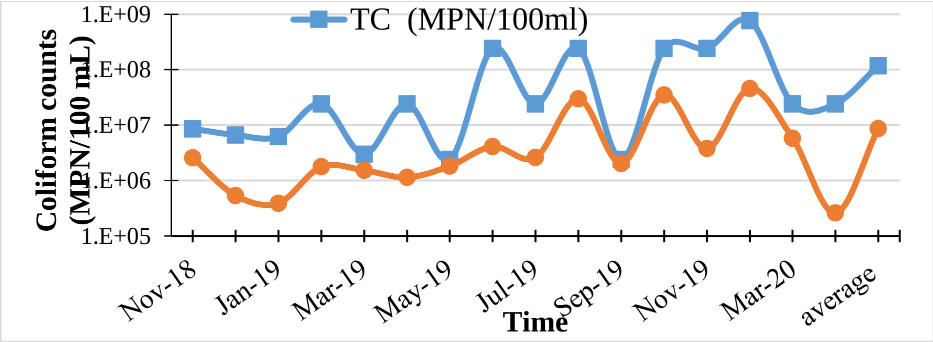


Fig. 8: Monthly Variation in Total coliform and *E. coli* Counts in Domestic Wastewater of Ibrahimpur Village

Characteristics of ground water samples of Muzaffarnagar area Physico-chemical analysis of pond

pH is one of the most important parameter in water chemistry and is defined as the negative of the base 10 logarithm of the molar concentration of hydrogen ion, and is measured as intensity of acidity or alkalinity on a scale ranging from 0-14. In natural waters, pH is governed by the equilibrium between carbon dioxide, bicarbonate and carbonates ions and in general, ranges between pH 4.5 to 8.5. Although pH has no direct impact on the health of consumers, it is one of the most important operational water quality parameter. BIS (2012) have prescribed pH value in the range of 6.5 to 8.5 for water used for drinking purpose. Moreover, the pH value prescribed vide the effluent standards notified vide G.S.R. 422(E) dated 19.05.1993 under Environment (Protection) Act, 1986 for discharge of effluents into inland surface water is 5.5 to 9.0. The pH of the analyzed water samples of study area varies from 6.7 to7.3.

Electrical conductivity (EC) is a measure of the ability of an aqueous solution to carry an electric current. This ability depends on the presence of ions; on their total concentration, mobility, and valence; and on the temperature of measurement (Arain et al., 2014). The electrical conductivity and dissolved salt concentrations are directly related to the concentration of ionized substance in water and may also be related to problems of excessive hardness and or other mineral contamination(Sajil Kumar & James, 2013). The overall range of the electrical conductivity varied between 570 µS/cm and 2050 µS/cm in the water samples. The results of in-situ analyzed parameters are presented below Fig. 9 (pH), 10(EC).

The DO, BOD, and COD concentrations in the pond water samples were in the range of 0 to 3.1 mg/l, 16-90 mg/l, and 56-380 mg/l respectively. The BOD concentration in the pond water was due to the influx of organics from the incoming domestic wastewater from the village habitation and is sufficient enough to bring down the DO in the pond to near zero. In few ponds, the DO detected in the samples may be because of thephoto synthetic activity of algae in the pond which will reduce to zero after sunset and the pond environment is not suitable for the aquatic species, especially fishes (Fig. 11)

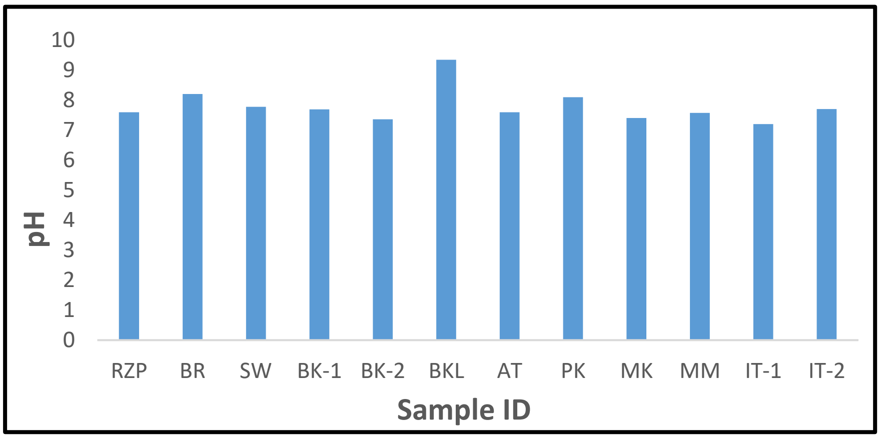


Fig. 9: pH of Muzaffarnagar Pond

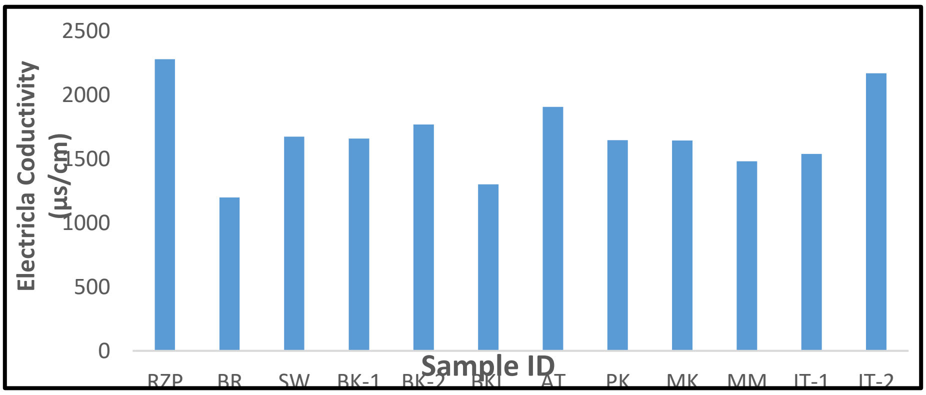


Fig. 10: Electrical Conductivity of ponds

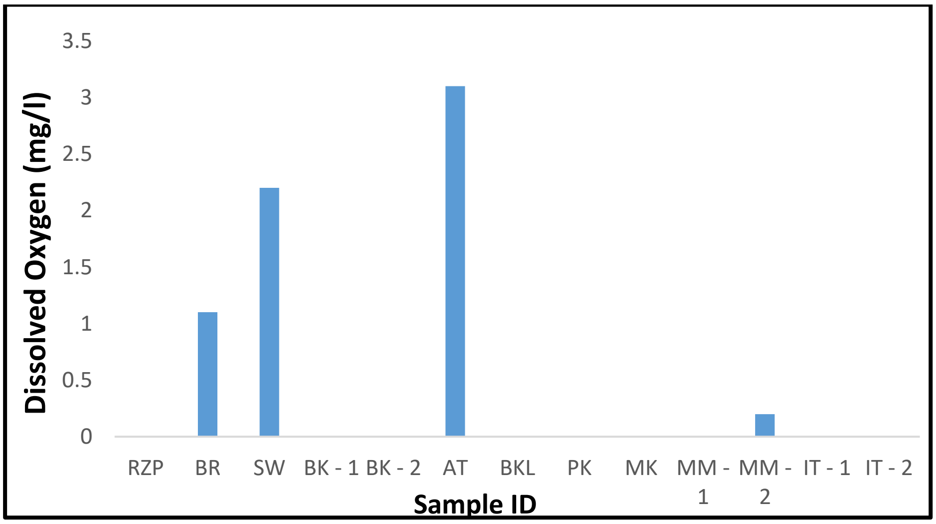


Fig. 11: DO of ponds

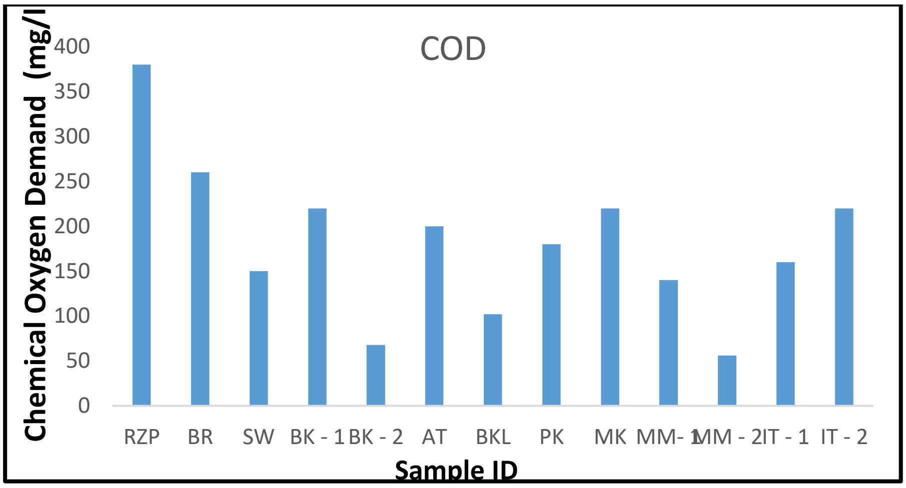


Fig. 12: COD of ponds

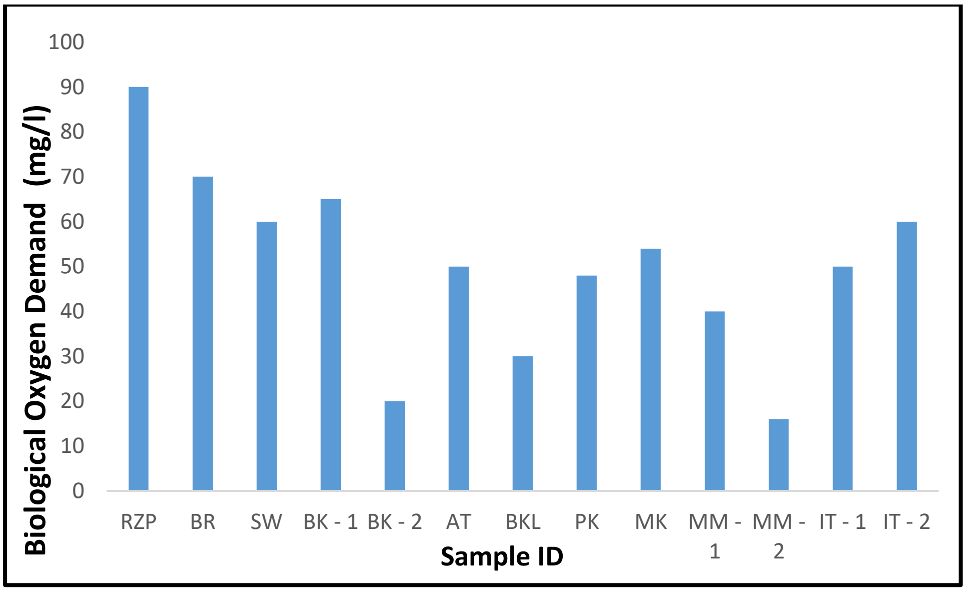


Fig. 13: BOD of Ponds

Performance Evaluation of Natural Treatment System

Overall performance of constructed wetland and floating wetland at Ibrahimpur village and Muzaffarnagar respectively was evaluated. It was observed that, the village pond is last in the treatment chain and the water quality of the pond was monitored to understand the overall improvement in water quality. It was observed that the complete system was able to significantly improve the overall water quality and making it more acceptable to the villagers for recreational activities and potentially suitable for usage, such as for irrigation water and groundwater recharge. The overall improvement in water quality was observed. The pH of Ibrahimpur pond ranges from 7.05 to 7.39 with an annual average value of 7.18±0.11. The average annual pH of the pond was 6.47% lower than the wastewater average annual pH. The pH range observed in the pond was near neutral and suitable for the pond ecology(Mor et al., 2017).The conductivity of the pond water during the observation period ranges from 1280 µs/cm to 2178 µs/cm. The average electrical conductivity of domestic wastewater before entering the treatment chain was 1820.83±289.68µs/cm and in the pond, the value comes down to 985.30±195.83 µs/cm. This reduction in overall EC was around 45.9% removal efficiency of Electrical conductivity. This decrease in conductivity was due to the removal of organics from the wastewater(Voutsis et al., 2015).The DO levels in the pond water ranges from 4.3 mg/L to 9.9 mg/L. The average annual DO in the wastewater was 0.64±0.32 mg/L and in the pond, the average annual DO was 5.92±1.68 mg/L indicating an 824% increase in dissolved oxygen levels. These values indicate good daytime DO levels in the pond water suitable for fisheries.

On the other hand, Muzaffarnagar ponds where floating wetland system was installed observed the significantly improved the quality of water in ponds. pH of ponds in 2017 ranged from 7.2 to 9.3 with average value 7.8±0.16 and in 2020, it ranged from 7.1 to 8.4 with average value 7.8±0.17. Reduction in pH was observed for most of the pond water samples and this may be due to decrease in the phytoplankton in the ponds(Dzwairo et al., 2006). The electrical conductivity of the pond water samples varied from 1303 to 2280 µS/cm in year 2017 and 656 to 2650 µS/cm in the year 2020. In the year 2017 TDS value was observed in the range of 810 to 1306 mg/l and in year 2020 TDS ranged from 424.3 to 1696 mg/l. TDS and conductivity signify the presence of dissolved salts in the water and no specific impact was visible. Dissolve Oxygen (DO), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are indicators of pollution status of the water body. For a healthy water body, DO should be high near saturation level and BOD values should be less than 3 mg/l. The average DO, BOD and COD of pond water samples in 2017 was 0.55±0.30 (range: non detectable - 3.1 mg/l), 51±6.1 (range: 16 - 90 mg/l), and 184±25.6 (range: 56 – 380 mg/l) respectively. In 2020, the average DO, BOD and COD values were 3.01±0.86 (range: non detectable – 8.9 mg/l), 71.7±20.0 (range: 9 - 200mg/l), and 254.2±68.7 (range: 40 – 680 mg/l) respectively. Improvement in DO values and reduction in BOD values was observed for most of the ponds after rejuvenation.

Further, eutrophic status of the ponds, defining the overall health of water body, was computed from the nutrient levels in the pond water. The CTSI values in 2017 ranged from 110 to 146 (Average value: 117.8±2.91) indication hypereutrophic condition. The condition changed to eutrophic status with average TSI value 82.8.8±2.69 (Range: 73 – 94). The change is eutrophic status is due to removal of organic and nutrient rich sludge accumulated at the bottom of the ponds (Goyal et al., 2021). It is desired to have oligotrophic or at least mesotrophic status but was not achieved for the rejuvenated as most of the ponds are receiving untreated sewage rich in nutrients and organics from the habitation(Fetouani et al., 2008).The high organics and nutrients in the pond water may be also attributed to the dumping of solid wastes line cow dung, household waste, etc., in the vicinity of ponds which get washed in the pond during rain spells. Therefore, apart from the infrastructure, awareness regarding cleanliness around pond among villagers is also the need of the hour to protect these water bodies.

Conclusions

In developing countries, like India, traditional sources of surface water, such as village ponds, have deteriorated. This study was conducted to evaluate the status of a number of village ponds to evaluate their restoration needs and potential for water use. The ponds were all rich in organic matter and nutrients due to loadings from domestic wastewater, livestock waste and village surface run-off. Because of this, ponds were mostly anaerobic/ anoxic due to microbial degradation of the organic matter preventing establishment of fisheries. Electrical conductivity was also generally high, limiting use for irrigation water. After installing NTS system in both the area, it was observed that organic load in ponds reduced. Ultimately some form of decentralised wastewater treatment, such as constructed and floating wetlands, are needed to reduce the loads of organic matter and nutrients entering from the villages and surrounding land. Moreover, rejuvenation of ponds in study area also led to the increase in ground water level as well.

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Economics and Environmental Benefits of Natural Wastewater Treatment Systems

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The conventional approach of sewerage infrastructure development has always favoured centralized systems, while adopting treatment technologies with a low land footprint and disposing of the treated effluent in adjoining water bodies. Adoption of Mechanized Treatment Systems (MTS) in the Indian context often lacks consideration of skilled technicians to operate the STPs, availability of electricity and expenses incurred during O&M. The incorporation of life cycle thinking across the continuum of sewerage infrastructure planning is lacking, resulting in several obstacles in achieving sustainability of the wastewater sector. India has several international commitments such as the Sustainable Development Goal (SDG) 6 'Clean Water and Sanitation' and SDG 11 'Sustainable Cities and Communities' and also national missions to deliver, such as Jal Jeevan Mission and Amrut 2. However, if the future infrastructure continues to be planned in a centralized manner operating on energy-intensive treatment technologies, the sustainability of wastewater treatment will be of crucial concern. Thus, to attain increased and efficient STP coverage in developing countries while adhering to various commitments towards the environment, adopting a decentralized infrastructure approach can be beneficial (Maniam et al., 2022; Kalbar and Lokhande, 2023).

Natural Treatment Systems (NTS) are a potential solution in this regard which are not prioritized due to a lack of understanding about its benefits. Hence, the possibilities of integrating NTS independently or in a hybrid fashion needs investigation. The O&M costs of MTS linearly increase with the BOD removal up to 30 mg/L. The escalation in costs is exponential as the outlet BOD crosses 30 mg/L due to the requirement of advanced technologies. However, the O&M cost of NTS such as Constructed Wetlands (CWs) is not significantly impacted for BOD removal beyond 30 mg/L. On the contrary, the land requirement for NTS CWs increases exponentially with reduction in outlet BOD. This makes the use of CWs (and other NTS) for secondary treatment more suitable in rural and peri-urban settings in a decentralized manner, where land availability is not a major constraint. The trade-offs between MTS and CWs show that each of the systems if used individually is suitable for only a specific local condition. Considering the trade-offs between MTS and NTS, the use of

MTS for initial BOD removal up to 30 mg/L using less land area and the subsequent use of CWs for achieving BOD removal beyond 30 mg/L in less cost is suggested. This approach of strategically utilizing the advantages of MTS and CWs to facilitate sustainable wastewater treatment is referred to as 'Hybrid Treatment System'. NTS or HTS are enablers of Circular Economy in the wastewater sector and also demonstrate greater resilience amidst climate change (Nika et al., 2020); however, their full-scale potential has not been assessed adequately.

The full-length article on the need and concept of 'Hybrid Treatment Systems' is published in 'Clean Technologies and Environmental Policy' and can be found on https://doi.org/10.1007/s10098-021-02034-x

Lack of clear goals and holistic consideration while planning results in fragmented actions by ULBs, and incoherent decision-making eventually causes resource wastage and inadequate service delivery (Heller et al., 2014). In this situation, using scenario planning while framing vision plans for the city can strengthen the government capacity to address water management problems strategically (Pot, 2019) and has potential to improve the decision-making in the water sector (Heller et al., 2014). In the present research, six scenarios have been envisaged (refer Figure 1) to facilitate sustainable and resilient sewage treatment. The scenarios are based on the regulatory norms on treatment water quality, implementation strategy for STPs and an appropriate combination of sewage treatment approaches adopted for urban and rural areas.

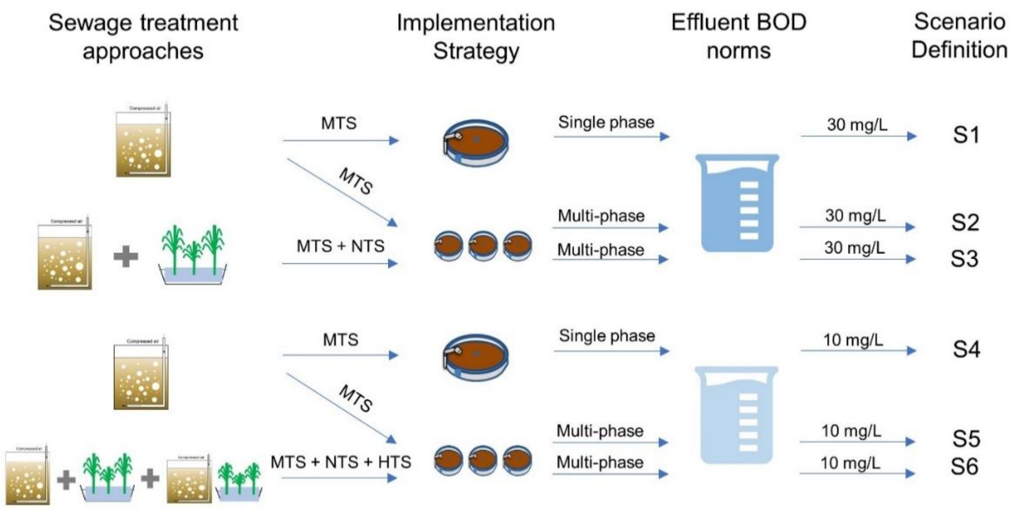

Fig 1. Scenarios defined for the present analysis

The first three scenarios are based on effluent BOD 30 mg/L whereas the next three scenarios are designed for effluent BOD 10 mg/L as mandated by the NGT. The first scenario is based on the current practice of implementing sewage treatment for a design life of 30 years. Regarding the technology choices, popular MTS such as ASP and SBR are considered to represent MTS. The successful operation of CWs has been demonstrated for over 30 years, making it a mature technology (Mitsch et al., 2023) And hence CWs are used to represent NTS. In the second scenario, MTS are assumed to be implemented in a phase-wise manner i.e. at time t=0 years, STP capacity serving projected population for initial 10 years is only considered to be constructed and operated. Successively, the STP capacity is enhanced every decade in this scenario to ensure maximum capacity utilization of STPs. In the third scenario, an appropriate combination of sewage treatment approaches is chosen to leverage the benefits of NTS. Scenarios 4, 5 and 6 are similar to scenarios 1, 2 and 3 respectively, except for the discharge standard of effluent BOD which is 10 mg/L. While comparing benefits of adopting NTS and phase-wise implementing strategy, S1 is considered the base scenario for S2 and S3, while S4 is assumed the base scenario for S5 and S6.

The full-length article published in 'Water Research' can be found on DOI: https://doi.org/10.1016/j.watres.2024.121710

Net Present Worth (NPW) method of Life Cycle Costing is used for computations. The detailed methodology can be found in IS 13174 Life Cycle Costing (Part 1 and 2). The LCC for the six scenarios has been computed in accordance with the cash flow diagrams. The LCC to plan 100% sewage treatment facilities treating up to 30 mg/L effluent BOD in India are INR 85 trillion in S1, while it is around INR 58 and 54 trillion for S2 and S3 respectively (refer Figure 5a). For the scenarios of achieving the stringent norms of 10 mg/L, the LCC are approximately INR 90, 63 and 60 trillion for S4, S5 and S6 respectively. Thus, merely implementing MTS in a phase-wise manner by creating and operating infrastructure only for the upcoming decade can result in around 30% cost reduction (refer Figure 2a). Further, the partial adoption of NTS for sewage treatment can reduce the LCC by around INR 3 to 4 trillion. In addition to the significant savings of 30% achieved by phase-wise implementation of MTS, incorporating NTS and HTS merely reduces the LCC by approximately 4% due to the trade-offs between land and energy costs. However, the potential benefits of integrating NTS and HTS are visible from the results of GHG emissions computed for all six scenarios.

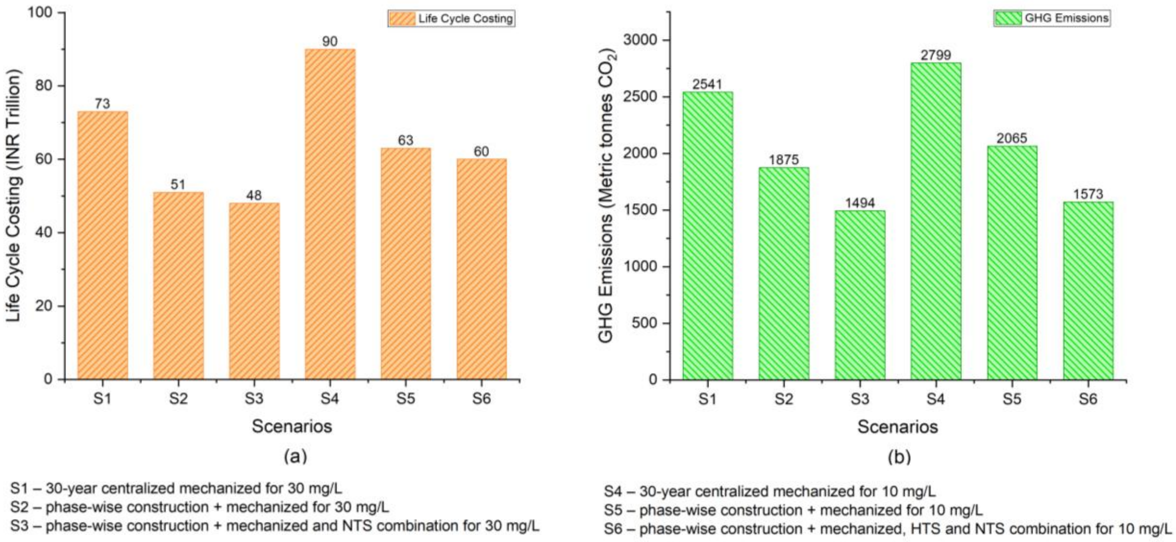

Fig. 2. Summary of life cycle computations for cost and GHG emissions

The GHG emissions for attaining 30 mg/L in S1, S2 and S3 are depicted in Figure 5b, which are approximately 2541, 1875 and 1494 Million Tonnes (MT)-CO_2, while for achieving effluent BOD of 10 mg/L, the resulting GHG emissions are approximately 2799, 2065 and 1573 MT-CO_2 for S4, S5 and S6 respectively. Attaining the stringent norms of effluent BOD 10 mg/L will emit around an additional 10% of GHG emissions. However, adopting phase-wise implementation of infrastructure will help reduce the GHG emissions in S2 and S5 by 26.3% compared to the respective base scenarios S1 and S4. Further, the adoption of a strategic combination of NTS, HTS and MTS in planning sewage treatment reduces the GHG emissions further by almost 15%, as evident from the results that 41.3% and 43.8% savings in GHG emissions are attained in S3 and S6 as compared to the respective base scenarios S1 and S4.

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Figure 3 shows the percent reduction in LCC and GHG emissions for the scenarios with respect to the base scenarios. For example, for a given parameter (either LCC or GHG), S2_S1 represents the percent reduction in S2 in comparison with S1. The values mentioned in the above discussion represent the average values for India; however, Figure 3 depicts the wide variation in percent reduction across different states. Thus, there is a stark difference between the cost savings and environmental benefits in the scenarios adopting combined treatment approaches. Hence, it is pertinent that investing in land by adopting NTS or HTS wherever feasible has multiple benefits. The maximum percent savings in LCC are observed in Uttarakhand and Himachal Pradesh, which might be associated with the adoption of deep-bed wetlands that have considerably reduced the land requirement, hence land cost. With respect to

GHG emissions, Bihar has maximum percent reductions in S3 and S6 i.e. Bihar will benefit from the adoption of hybrid sewage treatment approaches, which might be due to the greater share of rural population in Bihar, favoring a higher adoption of NTS. As S6 has effluent norm of BOD 10 mg/L, the adoption of NTS has greater economic and environmental benefits over MTS in S6 as compared to S3. Hence, there is a wide spread of percent savings in S6_S4. The wide spread in S6_S4 can be attributed to the states having significant rural population, or states having cheaper land rates, where the inclusion of NTS is significantly lowering the overall O&M costs in comparison to S5_S4.

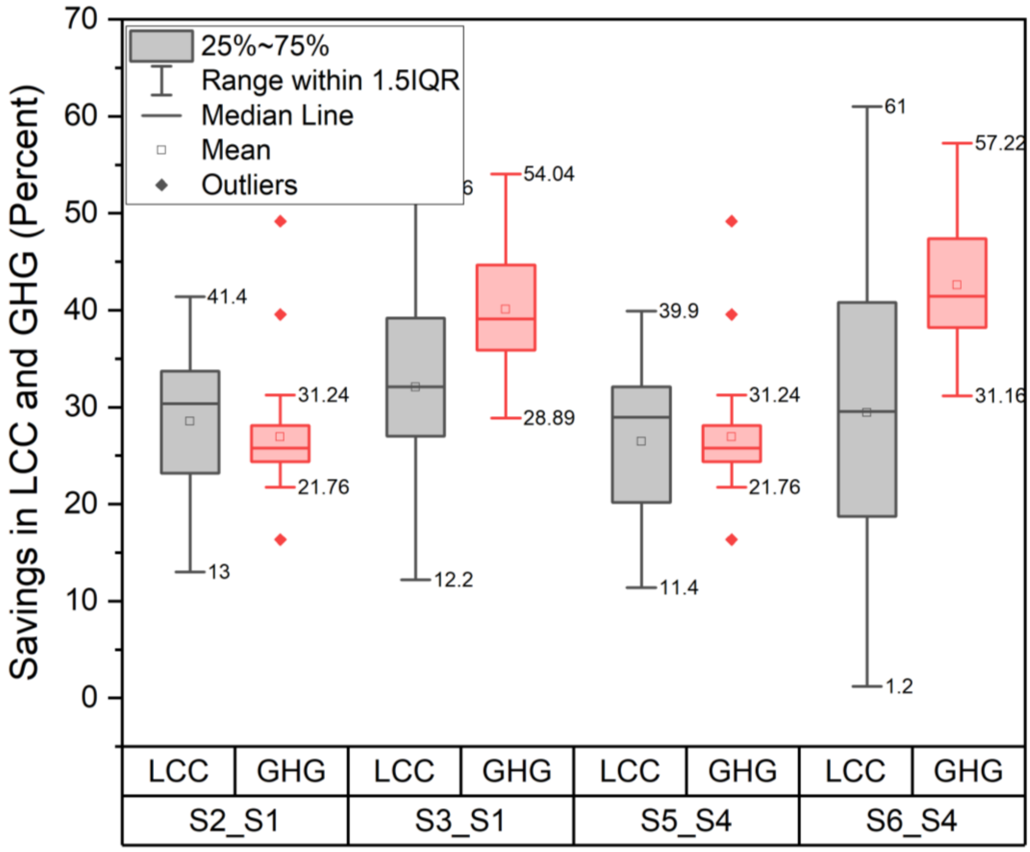

Fig 3: Statistical summary of % savings in LCC and GHG emissions across different states in India

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Further, the land, capital and O&M cost components for NTS, HTS and MTS constituting LCC across all Indian states are computed in analysis. It is observed that, the capital cost constitutes a minor share in LCC while it is the O&M and land cost majorly constituting LCC. The variation in cost components in rural and urban areas is due to the differences in percent adoption of sewage treatment approaches. The O&M of NTS and HTS and land cost for NTS are the prominent components of LCC in rural areas. The O&M requirement for NTS is relatively lower than HTS and MTS, hence, this operational cost will majorly be incurred on human labor, as against energy in MTS. In case of urban areas, the land cost for MTS followed by HTS majorly comprise LCC. Thus, land requirement is vital for sewage treatment irrespective of sewage treatment approach. However, if ULBs already have government-owned land and need not purchase it, the LCC will substantially be lowered.

The role of O&M costs is significant in overall project life, and lack of consideration of the same while planning is a prominent reason for non-sustenance of STPs in India. It is observed that the annualized O&M cost component when compared with the present-day investment, is equivalent to 149.6 and 108 % in S2 and S3 with respect to base scenario S1. Thus, there's almost 40 % decrease in O&M cost component if NTS are adopted partially. Further, this component is 121 and 57 % of the present-day investment in S5 and S6 respectively, which shows the significance of adopting HTS and NTS to plan the sewage treatment facilities for attaining 10 mg/L effluent BOD.

Centralized STPs are typically designed for a period of 30 years. However, due to lack of 100 percent network coverage in initial years and uncertainties in urban growth, the STPs practically receive very low flows for substantial years after their commissioning. For example, 87 MLD STP commissioned in 2010 at Nanded, in the state of Maharashtra, receives only 40 MLD (less than 50 percent) after 12 years. Thus, the conventional approach of centralized infrastructure planning results in severe underutilization of capacities in municipal STPs and wastage of resources. The present work puts forth the approach of reserving adequate land for future estimated sewage treatment capacity, but creating and operating the infrastructure only for the upcoming decade. This approach can improve the capacity utilization of STPs and also allow the upcoming infrastructure to better respond to future development (Kalbar and Lokhande, 2023) and scale down the financial risks in investment (Torre et al., 2021). Also, the sunk cost fallacies are known to hinder innovation in water sector (The Water Blog, 2019); however, a phase-wise approach in planning will lower the investments and risks, thereby overcoming this bottleneck in innovation. Also, this approach can reduce the per-capita cost of sewerage infrastructure, making it more affordable for the masses and ensuring greater coverage.

Significance of integrating NTS for planning STPs

India has a vast diversity in water availability with some states receiving abundant rainfall while others remaining water-stressed for most of the year. Further, irrigation water withdrawal has been identified to prominently influence water scarcity in India (Dai and Liu, 2023). In the face of water scarcity challenges, recycling or reclamation of wastewater can provide a reliable source of water supply, catering to the non-potable demands (Kakwani and Kalbar, 2020; Maniam et al., 2022).

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Low-cost nutrient removal in NTS can improve the effluent quality and facilitate wastewater recycling. Thus, NTS are a potential alternative to mitigate water scarcity, and can be planned in drought-prone rural areas. Moreover, the plant species, duckweed and algae can be harvested from CWs, DWP and WSP, respectively, which can further be used to create a chain of products and bio-based materials including energy. Thus, NTS provide substantial business opportunities due to the potential of resource recovery in terms of sludge, nutrients, plants, and energy (Asolekar et al., 2014), and there is a dire need to develop relevant business models which can sustain the STPs. In the wake of unanticipated rainfall and uncertainties due to climate change, the shift in dependence of agriculture from rainwater to treated wastewater can be beneficial in improving agricultural output, thereby improving the quality of life of the poverty-struck farmers. Additionally, NTS are appropriate alternatives in developing countries due to lesser energy requirements and, hence lowered dependence on electricity for operation. Local people can also be trained to operate the NTS, facilitating employment opportunities within the region. Thus, unlike MTS, NTS have greater applicability even in rural areas. In such circumstances, the states having high percentage of rural areas or low land rates can explore maximum feasibility of incorporating NTS.

Policy implications

Wastewater treatment involves land vs. energy trade-offs, and the land rate has a significant impact on decision-making while adopting NTS. Mell et al. (2023) have emphasized communicating the benefits of investing in natural solutions (with the residents, organizations and decision-makers) to guide fund allocation. The present research incorporates a long-term perspective; accounts for the context of implementing STPs whether urban or rural areas; and quantifies the benefits to people and environment through a life cycle perspective. This analysis is an attempt to communicate the benefits of integrating NTS while planning STPs to policymakers and decision-makers, that are presented in Table 2 in the form of policy measures. While hybrid configurations in terms of combination of centralized and on-site systems have been suggested by Eggimann et al. (2016) from sustainability perspective, the present work suggests adoption of hybrid approaches specifically for sewage treatment.Specially, the states and regions having high water stress can be identified and prioritized for implementing the proposed approaches.

Table 1: Suggested policy measures from the present research

Sr.	Policy	Description of policy measures	Benefits
1	Sewage treatment approaches and technology choices for STPs	A combination of approaches (MTS, HTS and NTS) and appropriate technologies should be adopted instead of one technology for all STPs.	Infrastructure can benefit from the trade-offs between different approaches.
2	Implementation strategy for sewage treatment infrastructure	Land should be purchased or reserved for sewage treatment by the ULBs for 30 years; however, construction and operation of STPs should be planned in a phase-wise manner for design capacity only corresponding to the upcoming decade.	30% savings in life cycle cost and 25.6% savings in GHG emissions can be achieved through phase-wise implementation.

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Sr.	Policy	Description of policy measures	Benefits
3	Procuring land for sewage treatment	The guidelines for planning new STPs should focus on maximising adoption of NTS and HTS; hence, investing in land should be considered if needed.	Lower dependence on mechanized treatment will lower life cycle costs, maximize natural treatment and ensure sustainability.
4	Provisioning of O&M funds for STPs	Instead of spending the entire funding as capital investment, partial fund can be kept aside (as savings) for the recurring O&M expenses in the coming years.	Provisioning for O&M funds will sustain the STPs for a longer time.
5	Carbon tax	Increase the carbon tax such that it constitutes a significant share of O&M charges; explore the possibility of telescoping carbon taxing depending on per MLD energy requirements.	Facilitate the adoption of cleaner technologies and decentralized systems for sewage treatment.

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Technology Selection for Eco-Prudent Solutions Using JalVishwa

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JalVishwa is first of its kind multi-criteria decision support tool for the selection of an appropriate wastewater treatment technology. This tool has an integrated module for computing life cycle costs of sewage treatment technologies.

The salient features of the tool are:

1. Multiple criteria inclusion facilitating holistic decision making.
2. Decision making framework encompassing indicators from life cycle thinking
3. Flexibility with respect to technology and indicator selection
4. Scope of including criteria weighs for scenario-based decision making
5. Dynamic life cycle costing tool facilitating location-specific economic assessment
6. Guidance to decision-makers towards achieving circular economy in the water sector sector.

Using this freely available tool can aid the urban local bodies in implementing national schemes such as Swacchha Bharat Mission, Jal Jeevan Mission, AMRUT 2.0 and accordingly plan for fund allocation. The tool can be used by urban local bodies, planners, practitioners and researchers.

The tool can be accessed using the link below: jalvishwa-iitb.github.io

The YouTube tutorials can be accessed on the following link: https://youtube.com/playlist?list=PLhUEOeQI5cNuVk6ZwVWBmc4cMhBs1enPA&si=lKuUAZVSlXI2q41G

Constructed Wetlands (Phytoremediation)- Passive systems

Er. Gangadhar Reddy
CEO
BlueDrop Enviro Pvt Ltd.
Hyderabad

Introduction

Wetlands have been used informally for water treatment for thousands of years. This knowledge is formalized into an applicable technology by various researchers/firms and institutions since late 1950s. Since then, there has been rapid growth and adaptation of this technology worldwide in both the municipal and industrial sectors. Early systems were more of horizontal/saturated (surface flow) flow across the wetland basin, and these were very much reliant on the diffusion of air from the atmosphere into the bed to 'fuel' oxygen driven microbial degradation.

Over the past 20 years the increased demand for more sustainable, low carbon footprint water treatment solutions has led to a sharp rise in the use of constructed Wetlands with a parallel increase in understanding how these systems function and can be optimized to provide much higher levels of treatment. Subsequent and ongoing client driven innovation has led to a range of different wetland system types and designs which can provide high levels of treatment across a broad range of effluents from the municipal and industrial sectors.

We now see wetland systems capable of treating raw sewage right through to discharge and including full sludge management. There are over 1400 systems deployed by BlueDrop and its partners across the Globe. In India, BlueDrop alone has implemented over 70 wetland systems to address challenges that are one of their kind.

Wetland Solution with Aerated Treatment Wetlands

All the success stories we mentioned about were implemented as Passive Wetland systems mostly sub- surface flow with Horizontal or Vertical flows. Our systems have had larger foot print as they were designed to NOT clog, have consistency in treatment results and to meet environmental norms.

So, The Need

Standard types of passive wetlands rely on the diffusion of oxygen from the air into the water column, which is a very slow process. This lack of oxygen transfer slows the removal of organic compounds and limits the removal of ammonia from wastewaters. Also, the larger footprint made the systems unviable in terms cost and space requirements. Further, their effective life was also limited and the systems were somewhat static with no controls available for the operator.

Solution

Aerated Treatment Wetland systems rely on the ability to inject small quantities of air in a very uniform pattern throughout the wetland bed. This allows operator control over the entire oxidation process during wastewater treatment while only using a small fraction of the energy required by conventional STPs.

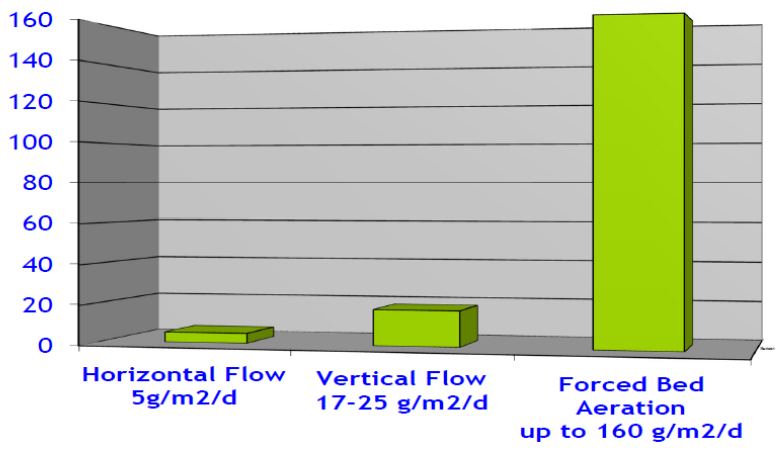
Intermittent operation of the aeration system can be fined-tuned to optimize treatment goals such as total nitrogen removal.

Originally developed in 1997 as a patented process in the United States, Aerated wetlands are now being used in Belgium, Brazil, Canada, China, Colombia, Denmark, France, Germany, India, Ireland, Italy, Martinique, Mexico, the Netherlands, Qatar, the United Arab Emirates, the United Kingdom and other countries due to the wide- ranging benefits of optimized, aerated wetlands.

Benefit

Aerated wetlands are 3 to 5 times smaller than conventional passive wetlands. The reduced area saves construction costs and means that wetlands can be used in limited land areas. The systems do not produce excess sludge like conventional mechanical treatment plants and only use about 10% of the energy required for a comparable activated sludge process. Treatment of high-strength wastes is also popular, with numerous systems operating for aircraft de-icing, oil & gas, chemical manufacturing, food & beverage, mining and landfill leachate applications.

The chart below provides a comparison of oxygen transfer rates seen in passive wetlands and aerated systems using Aerated Wetlands System.



As demonstrated above, aeration significantly enhances aerobic mcrobial degradation, boosting treatment capacity by up to ten times per unit area compared to passively operated systems. At BlueDrop, we construct vertical flow systems that distribute effluent across the entire surface area of the wetland cell. This results in a much lower hydraulic and contaminant load per square meter, leading to a reduced clogging rate, longer lifespan, and more efficient biomass development throughout the wetland cell.

Regular inspection and maintenance are crucial to ensure the proper functioning of diffusers and aerators. Clogging from sediment, biofilm, and other debris can substantially decrease oxygen transfer efficiency. We periodically clean and replace diffusers to maintain efficient operation. Additionally, we inspect the air distribution network, including pipes and manifolds, for leaks, blockages, and wear. Ensuring the integrity of these components is essential for maintaining uniform aeration throughout the wetland bed.

The effluent flows downward through the bed, washing over the microbial biomass that grows on the media and effectively degrades BOD and ammonia. This process is driven by the oxygen carried in the air moving counter currently upward from the bottom of the bed.

Conclusion

Their simplicity, with few or no moving parts make them a reliable, robust treatment solution with low maintenance and power requirements resulting in low lifetime costs compared to the mechanical treatment alternatives.

Why Use Aerated Treatment Wetland Systems instead of Passive Wetlands...

- Low footprint than passive systems*[1]
- Lower capital costs
- Mitigated risk of clogging
- Effective Ammonia removal
- Prevents biomass/mineral/inorganic accumulation
- Flexible and Scalable**[2]
- 30+ years of effective life
- Robust operations
- Flexible for modular design***[3]
- Quick to construct and commission (2.4 MLD built n commissioned < 3 months)

1. Many wetland systems in India are poorly designed; it is evident by the fact that many have clogging issues, poor treatment. It is seen most wetland implementations add chlorination mechanism which no one gets to monitor how much chlorine is added. It’s a known fact

that very rarely operators set up dichlorination; unmonitored chlorination is a serious concern for the aquatic life and microflora in the water.

2. Varying loads of BOD/TSS and/or varying volumes of treatment can easily be handled by aerated systems without changing any infrastructure but altering the aeration cycle times. Systems that are designed keeping in view of a 20/30-year horizon which often receive 20% to 40% load to begin with can be easily be managed without incurring full load operational expenses.

a. We have implemented an aeration system at Hyderabad which is designed to treat a 200 KLD and also a 2.40 MLD without needing any additional arrangements/operators but simply changing the aeration cycle.

3. Systems can be designed in a modular way; one can implements a wetland cell to treat a 500 KLD or 1 MLD or 2 MLD and can add a similar or lesser or higher capacity by developing another wetland cell for the required capacity.

BlueDrop- Aerated Wetlands Case Study:

Well-designed & engineered wetland systems can handle high strength wastewaters. At BlueDrop we have treated waste streams which have BOD levels ranging from 100 to 1500, COD levels from a 100 to 6000, TSS levels 100 to 1200.

NCD Vivanta Central Court (150 KLD): Commissioned December 2021

A luxury apartment community at Mokilla. The Developer having seen the complex and struggle some conventional systems in various residential apartment communities have come to a conclusion to adopt a better and environment friendly technology. We have utilized part of their garden areas to create the Aerated Wetlands and have commissioned the system in late 2021. System has been working steadily with low maintenance and high aesthetics with zero odour. Residents enjoy being around this people friendly STP.

Design Capacity: 150 KLD

Type of water: Domestic Wastewater

Address: Mokila near Sankarapally

Treatment units:

- Manual Bar Screen chamber (10mm screen)
- 3 chamber Holding tank (150 KLD)
- Wetland cells 2 each 75 SQM
- Treated Water Collection Sump (2 partitions)

- Tertiary treatment (Ozonator)

Parameters	BOD	COD	TSS	Sulphate (SO4)	Chloride	O&G	pH
Inlet	178	273	125	85	156	12	6.5
Treated	<10	<10	<10	<15	130	<5	7.5

Sewage & Wastewater at Hyderabad for NISA, Hakimpet:

Design Capacity: 150 KLD

Type of water: Domestic (Training/residential quarters, Kitchen, Canteen)

Address: NISA, Hakimpet, Hyderabad, Telangana - 500078

Treatment units:

- Manual Bar Screen chamber (10mm & 6 mm screens)
- Wet-well (30 KLD)
- Holding tanks -2 No each (150 KLD pre-existing tanks, repurposed)
- Aerated Wetlands Cells: 2 Nos each 100 SQM
- Treated water collection sump

Parameters	BOD	COD	TSS	Sulphate	Chloride	O&G	pH
Inlet	186	281	48	75	147	8	7.12
Treated	8	47	12	53	126	<5	7.34

An institutional residential set up which has a defunct Sewage Treatment Plant wanted to set up a new system. The treated water is the only source they have to water their lush green lawns of their Golf Course. BlueDrop proposed extremely optimized solution utilizing their existing tanks etc and just adding two Aerated Wetlands.

BlueDrop demonstrated a great success with the setting up all new Aerated Wetlands system within 60 working days and has taken care of the golf course needs through the hot summer. System was commissioned on March 15, 2020.

Sewage & Wastewater at the Heartfulness World HQ, Kanha Village for SMSF & SKGL:

Design Capacity: 2.40 MLD

Type of water: Domestic (Apartments, Kitchen, Canteen, Group Toilet blocks)

Address: SMSF/SKGL, 13-110 Kanha Village, Ranga Reddy dist, Telangana - 509325

Treatment units:

- Manual Bar Screen chamber (10mm & 6 mm screens)
- Wet-well (400 KLD)
- Holding tank 1 (1600 KLD Newly built)
- Holding tank 2 (600 KLD pre-existing tank, repurposed)
- Aerated Wetland Cells: 2 Nos;1000 SQM Each
- Treated water collection sump

Parameters	BOD	COD	TSS	Sulphate	Chloride	TDS	pH
Inlet	187.70	232.50	133.00	165	185	1248	6.30
Treated	<5.00	21.25	10.00	83.5	171.48	906.00	7.76

A mega integrated township with residences, kitchens, canteens, training halls, huge congregation facilities, mega toilet blocks etc with a challenging scenario of hosting 50,000+ at times and scaling down to 20,000 or 10,000 or just residents who are in fewer thousands. The system receives varying volumes of wastewater ranging from 200 KLD to 2,400 KLD. BlueDrop has demonstrated phenomenal success in setting up the Aerated Wetlands in a span of 60 calendar days to meet a huge worldwide congregation deadline. The Aerated Wetland System performed the work like a breeze delivering absolute clear water meeting the PCB norms. System was commissioned on January 27, 2020.

Constructed Wetlands: Experience in Hilly Regions

Dr. Dinesh Poswal
Director; Rebound Enviro Tech Pvt. Ltd.

Constructed wetlands are engineered systems designed to mimic the natural processes of wetlands to treat wastewater, storm-water, or runoff. These systems are used for water purification, flood control, habitat creation, and recreational purposes. They utilize a combination of physical, chemical, and biological processes to remove contaminants from water. Constructed wetlands provides several benefits as a treatment options, including Water Quality Improvement, Habitat Creation, Flood Control, Aesthetic and Recreational Value, Cost-Effective, etc.

Habitations in hilly regions require careful planning and sustainable practices to overcome the challenges posed by the terrain and climate. By leveraging traditional knowledge, modern technology, and community resilience, these areas can create livable, thriving environments that preserve their natural beauty and ecological balance. Further, wastewater treatment in hilly regions presents unique challenges due to the topography, accessibility issues, and environmental sensitivity. Effective solutions must be adaptable to the terrain, resource-efficient, and environmentally sustainable.

To keep in mind of the intact challenges associated with hilly terrane – specific strategies and technologies for wastewater treatment need to be implemented. In such circumstances, Decentralized Wastewater Treatment Systems, including, On-Site Treatment systems and Cluster Systems are most adaptive. Among several technological alternatives, Natural and Engineered Wetlands provides one of the appropriate solution which may best fit in such topography and provide high levels of treatment to wastewaters.

Further, constructed wetlands in hilly regions offer a multifaceted approach to environmental management, addressing water quality, flood control, habitat creation, and more. They provide an eco-friendly, cost-effective solution that leverages natural processes to benefit both the environment and local communities. In addition, effective wastewater treatment in hilly regions requires a combination of appropriate technologies, innovative design, and community engagement. By leveraging decentralized systems, natural treatment processes, and resource recovery, it is possible to manage wastewater sustainably, even in challenging terrains. These approaches not only protect the environment but also enhance the quality of life for residents in hilly areas.

With above benefits of engineered natural treatment systems, several sewerage schemes have been designed and implemented across the State of Himachal Pradesh in last five years under following categories:

1. Decentralized sewerage systems for leftover areas of the towns aimed to upgradation of existing sewerage systems.
2. Upgradation of existing sewage treatment facilities to meet the upgraded wastewater disposal norms prescribed as per direction of NGT, GoI.
3. Establishment of wastewater reuse based facilities for various towns.
4. Providing new sewerage systems for rural areas communities.
5. Establishment of Fecal Sludge and Septage Management (FSSM) facilities based on constructed wetlands aimed to provide complete sanitation facilities for towns and village communities.

In order to achieve complete sanitation system for hilly regions integrates various components tailored to the local environment, ensuring effective wastewater treatment, resource recovery, and sustainable management. By combining traditional practices with modern technologies in the shape of integrated engineered natural treatment systems, these systems can provide reliable, efficient, and eco-friendly sanitation solutions.

After a careful planning and comprehensive approach that considers environmental, hydraulic, and biological factors, systematic design process and tailoring the system to the local context - constructed wetlands have been designed and implemented across the state of Himachal Pradesh to provide effective and sustainable wastewater treatment solutions. The capacities of various treatment systems based of engineered natural processes ranges from 5 KLD to 3.00 MLD – which proves that such systems may be implemented in a wide range of communities. Some of sewage treatment facilities based on the engineered natural processes implemented across the State of Himachal Pradesh have been provided in Annexure.

Annexure: Details of Various Sewage Treatment facilities based on Engineered Natural Treatment Process implemented across the State of Himachal Pradesh

S. No.	Parameters	Remarks from State Government
A.	**200 KLD Sewage Treatment Plant, Dharamshala, Distt. Kangra H.P.**	
1.	Name of the city	Dharamshala
2.	Population as per Census 2011	1500 (Population Served)
3.	Current Population	1500 (Population Served)
4.	Current wastewater generation	180 KLD
5.	Characteristics of wastewater	BOD ≤ 350ppm, COD ≤ 700ppm, TSS ≤ 650ppm, PH: 6.5-8.5, TKN ≤30ppm, P≤10ppm
6.	Name of the STP /Technology	200 KLD STP Old Chadi Road, Dharamshala, Distt. Kangra, H.P.
7.	Name of the plants used, if any	*Canna Indica*
8.	Year of commission	Year 2018
9.	Time period of construction	1 Year
10.	Name of the scheme/funding agency	Dharamsala Smart City Ltd.
11.	Design capacity	200 KLD
12.	Actual utilization	200 KLD
13.	Current population covered	1500 (Population Served)
14.	Design Year	15 Year Period
15.	Design population	2500 Souls
16.	Treatment efficiency (BOD, COD, TSS, TDS, N, P)	BOD ≤ 10ppm, COD ≤ 50ppm, TSS ≤ 20ppm, PH: 6.5-8.5, TKN ≤5 ppm, P ≤ 2ppm
17.	Components of STP (Name of the units)	Primary Treatment Unit, Multi-Baffled Anaerobic Reactor (MBAR), Constructed Wetlands, Multi-Media Filter (MMF), Chlorine Contact Tank (CCT)
18.	Total Built-up area, in sq.m	500 Squire Meter
19.	Capital cost	70 Lakh
20.	O&M cost/year	12 Lakh (Including STP and Sewerage Network)

S. No.	Parameters	Remarks from State Government
21.	% of O&M charges collected through user charges/tax etc.	JSV Collected user charges collectively for whole city (50% of water bill cost)
22.	Labour requirement	4 Persons (Including STP and Sewerage Network)
23.	Details of user charges/taxes, Pl. specify	JSV Collected user charges collectively for whole city (50% of water bill cost)
24.	Advantages & disadvantages	
	✓ **Robust:** It is stable under load variations, insensitive to temporary limitation and provides consistent treatment results especially for treatment of sewages. ✓ **Efficient:** It does not generate solids and does not require solid (sludge) handling units. ✓ **Zero Energy:** It does not require any electricity to operate the STP, therefore, no environmental impact (negative green house impact). ✓ **Foot-print:** Space of any shape can be utilised and will be looks like a ornamental garden. ✓ **Cost:** It requires 50% lower capital cost and zero O&M costs. ✓ **Flexible:** Existing STPs can be upgraded easily with Constructed Wetland as a treatment facility to meet desired the compliance. ✓ **Trouble Free:** It has no O&M, and no recurring annual cost as compared to the conventional systems. ✓ **Expandable:** STPs being established on modular approach and can be commissioned at zero flow and can be expended according to the need. ✓ **Single Pass Process:** No return sludge stream required hence no smell. ✓ **Load Responsive:** Actively sloughed bio-film gradually responds to load fluctuations.	
25.	Recycle/reuse/disposal details of treated wastewater, if any	Currently no reuse available. Treated wastewater disposed in nearby surface running water body.
26.	Revenue generated through recycle/reuse, if any	Not Available
27.	Sludge generation, if any and its management	No sludge generated
28.	Sludge recycle/reuse/Disposal details, if any	No sludge generated
29.	STP sketch/layout drawing, if available	

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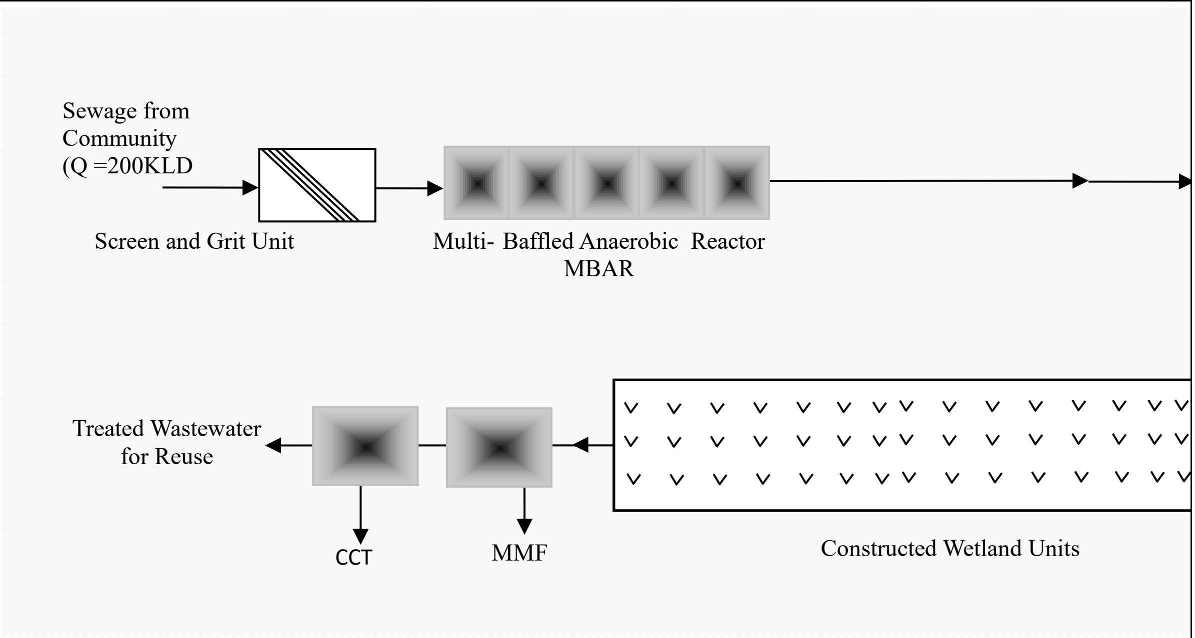
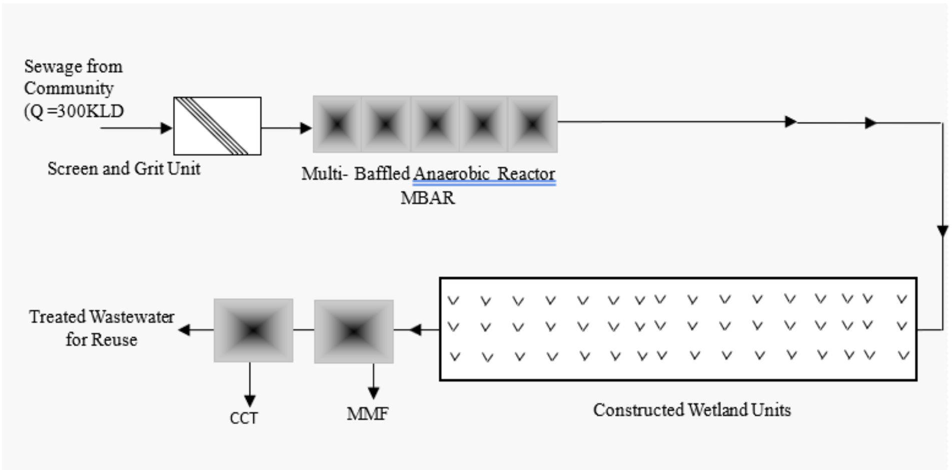
<tr><th>S. No.</th><th>Parameters</th><th>Remarks from State Government</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><td>30.</td><td>Photos</td><td></td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>31.</td><td>Performance of the plant</td><td>STP constantly performing well since of its establishment.</td></tr>
<tr><td>32.</td><td>Any other remarks</td><td>Absolutely trouble-free operation and management.</td></tr>
</table>

Sl. No.	Parameters	Remarks from State Government
B.	**30 KLD Sewage Treatment Plant, Dharamshala, Distt. Kangra H.P.**	
1.	Name of the city	Dharamshala
2.	Population as per Census 2011	200 (Population Served)
3.	Current Population	200 (Population Served)
4.	Current wastewater generation	25 KLD
5.	Characteristics of wastewater	BOD $\leq$ 350ppm, COD $\leq$ 700ppm, TSS $\leq$ 650ppm, PH: 6.5-8.5, TKN $\leq$30ppm, P$\leq$10ppm
6.	Name of the STP /Technology	30 KLD STP Ramnagar, Dharamshala, Distt. Kangra, H.P.
7.	Name of the plants used, if any	*Canna Indica*
8.	Year of commission	Year 2018
9.	Time period of construction	1 Year
10.	Name of the scheme/funding agency	Dharamsala Smart City Ltd.
11.	Design capacity	30 KLD
12.	Actual utilization	30 KLD
13.	Current population covered	200 (Population Served)
14.	Design Year	15 Year Period
15.	Design population	300 Souls
16.	Treatment efficiency (BOD, COD, TSS, TDS, N, P)	BOD $\leq$ 10ppm, COD $\leq$ 50ppm, TSS $\leq$ 20ppm, PH: 6.5-8.5, TKN $\leq$5 ppm, P $\leq$ 2ppm
17.	Components of STP (Name of the units)	Primary Treatment Unit, Multi-Baffled Anaerobic Reactor (MBAR), Constructed Wetlands, Multi-Media Filter (MMF), Chlorine Contact Tank (CCT)
18.	Total Built-up area, in sq.m	150 Squire Meter
19.	Capital cost	15 Lakh
20.	O&M cost/year	3.5 Lakh (Including STP and Sewerage Network)
21.	% of O&M charges collected through user charges/tax etc.	JSV Collected user charges collectively for whole city (50% of water bill cost)

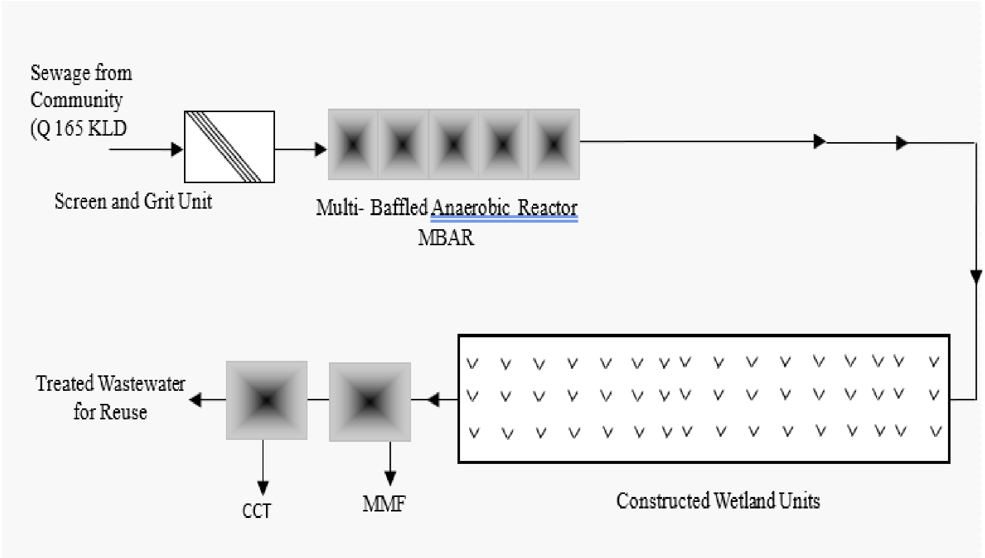
Sl. No.	Parameters	Remarks from State Government
22.	Labour requirement	2 Persons (Including STP and Sewerage Network)
23.	Details of user charges/taxes, Pl. specify	JSV Collected user charges collectively for whole city (50% of water bill cost)
24.	Advantages & disadvantages	
	As above	
25.	Recycle/reuse/disposal details of treated wastewater, if any	Currently no reuse available. Treated wastewater disposed in nearby surface running water body.
26.	Revenue generated through recycle/reuse, if any	Not Available
27.	Sludge generation, if any and its management	No sludge generated
28.	Sludge recycle/reuse/Disposal details, if any	No sludge generated
29.	STP sketch/layout drawing, if available	
		
30.	Photos	

Sl. No.	Parameters	Remarks from State Government
		
31.	Performance of the plant	STP constantly performing well since of its establishment.
32.	Any other remarks	Absolutely trouble-free operation and management.

Sl. No.	Parameters	Remarks from State Government
C. 165 KLD Sewage Treatment Plant, Dharamshala, Distt. Kangra H.P.		
1.	Name of the city	Dharamshala
2.	Population as per Census 2011	1200 (Population Served)
3.	Current Population	1200 (Population Served)
4.	Current wastewater generation	130 KLD
5.	Characteristics of wastewater	BOD $\leq$ 350ppm, COD $\leq$ 700ppm, TSS $\leq$ 650ppm, PH: 6.5-8.5, TKN $\leq$30ppm, P$\leq$10ppm
6.	Name of the STP /Technology	165 KLD STP Chellian, Dharamshala, Distt. Kangra, H.P.
7.	Name of the plants used, if any	*Canna Indica*
8.	Year of commission	Year 2020
9.	Time period of construction	1 Year

Sl. No.	Parameters	Remarks from State Government
10.	Name of the scheme/funding agency	Dharamsala Smart City Ltd.
11.	Design capacity	165 KLD
12.	Actual utilization	165 KLD
13.	Current population covered	1200 (Population Served)
14.	Design Year	15 Year Period
15.	Design population	1500 Souls
16.	Treatment efficiency (BOD, COD, TSS, TDS, N, P)	BOD ≤ 10ppm, COD ≤ 50ppm, TSS ≤ 20ppm, PH: 6.5-8.5, TKN ≤5 ppm, P ≤ 2ppm
17.	Components of STP (Name of the units)	Primary Treatment Unit, Multi-Baffled Anaerobic Reactor (MBAR), Constructed Wetlands, Multi-Media Filter (MMF), Chlorine Contact Tank (CCT)
18.	Total Built-up area, in sq.m	400 Squire Meter
19.	Capital cost	80 Lakh
20.	O&M cost/year	8 Lakh (Including STP and Sewerage Network)
21.	% of O&M charges collected through user charges/tax etc.	JSV Collected user charges collectively for whole city (50% of water bill cost)
22.	Labour requirement	4 Persons (Including STP and Sewerage Network)
23.	Details of user charges/taxes, Pl. specify	JSV Collected user charges collectively for whole city (50% of water bill cost)
24.	Advantages & disadvantages	
	✓ As above	
25.	Recycle/reuse/disposal details of treated wastewater, if any	Currently no reuse available. Treated wastewater disposed in nearby surface running water body.
26.	Revenue generated through recycle/reuse, if any	Not Available
27.	Sludge generation, if any and its management	No sludge generated
28.	Sludge recycle/reuse/Disposal details, if any	No sludge generated

Sl. No.	Parameters	Remarks from State Government
29.	STP sketch/layout drawing, if available	

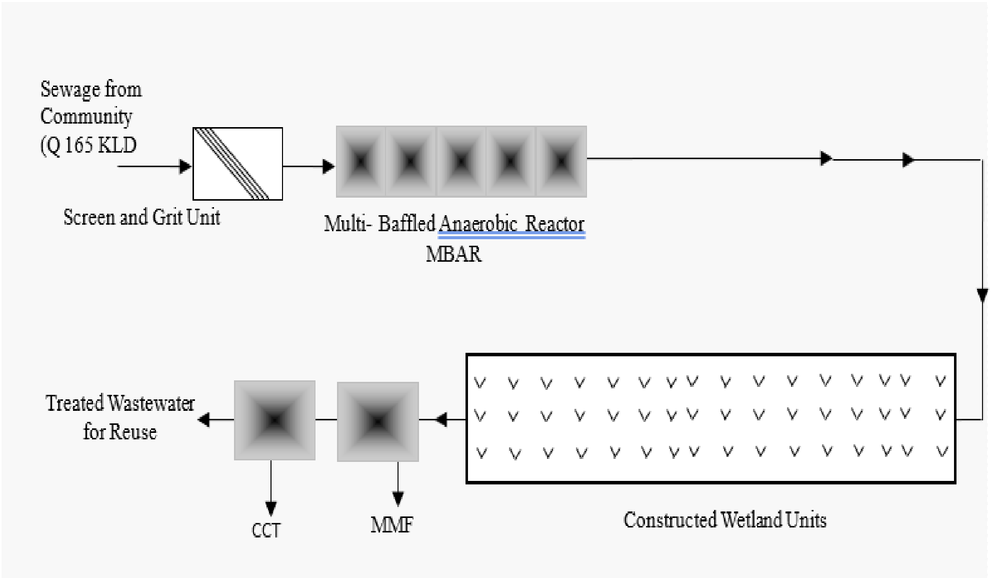


30.	Photos	
		
31.	Performance of the plant	STP constantly performing well since of its establishment.
32.	Any other remarks	Absolutely trouble-free operation and management.

Sl. No.	Parameters	Remarks from State Government
D. 55 KLD Sewage Treatment Plant, Dharamshala, Distt. Kangra H.P.		
1.	Name of the city	Dharamshala
2.	Population as per Census 2011	300 (Population Served)
3.	Current Population	300 (Population Served)
4.	Current wastewater generation	40 KLD
5.	Characteristics of wastewater	BOD $\leq$ 350ppm, COD $\leq$ 700ppm, TSS $\leq$ 650ppm, PH: 6.5-8.5, TKN $\leq$30ppm, P$\leq$10ppm
6.	Name of the STP /Technology	55 KLD STP Bhagsu, Dharamshala, Distt. Kangra, H.P.

Sl. No.	Parameters	Remarks from State Government
7.	Name of the plants used, if any	*Canna Indica*
8.	Year of commission	Year 2020
9.	Time period of construction	1 Year
10.	Name of the scheme/funding agency	Dharamsala Smart City Ltd.
11.	Design capacity	55 KLD
12.	Actual utilization	55 KLD
13.	Current population covered	300 (Population Served)
14.	Design Year	15 Year Period
15.	Design population	500 Souls
16.	Treatment efficiency (BOD, COD, TSS, TDS, N, P)	BOD ≤ 10ppm, COD ≤ 50ppm, TSS ≤ 20ppm, PH: 6.5-8.5, TKN ≤5 ppm, P ≤ 2ppm
17.	Components of STP (Name of the units)	Primary Treatment Unit, Multi-Baffled Anaerobic Reactor (MBAR), Constructed Wetlands, Multi-Media Filter (MMF), Chlorine Contact Tank (CCT)
18.	Total Built-up area, in sq.m	200 Squire Meter
19.	Capital cost	20 Lakh
20.	O&M cost/year	4 Lakh (Including STP and Sewerage Network)
21.	% of O&M charges collected through user charges/tax etc.	JSV Collected user charges collectively for whole city (50% of water bill cost)
22.	Labour requirement	2 Persons (Including STP and Sewerage Network)
23.	Details of user charges/taxes, Pl. specify	JSV Collected user charges collectively for whole city (50% of water bill cost)
24.	Advantages & disadvantages	
	✓ As Above	
25.	Recycle/reuse/disposal details of treated wastewater, if any	Currently no reuse available. Treated wastewater disposed in nearby surface running water body.
26.	Revenue generated through recycle/reuse, if any	Not Available

Sl. No.	Parameters	Remarks from State Government
27.	Sludge generation, if any and its management	No sludge generated
28.	Sludge recycle/reuse/Disposal details, if any	No sludge generated
29.	STP sketch/layout drawing, if available	



Sl. No.	Parameters	Remarks from State Government
E. 2.83 MLD Sewage Treatment Plant, Jwalamukhi Town, Distt. Kangra H.P.		
1.	Name of the city	Jwalamukhi Town
2.	Population as per Census 2011	24000 (Population Served)
3.	Current Population	24000 (Population Served)
4.	Current wastewater generation	2.83 MLD
5.	Characteristics of wastewater	BOD $\leq$ 30ppm, COD $\leq$ 100ppm, TSS $\leq$ 100ppm, PH: 6.5-8.5, TKN $\leq$15ppm, P$\leq$5ppm
6.	Name of the STP /Technology	2.83 MLD STP 24000, Distt. Kangra, H.P.
7.	Name of the plants used, if any	*Canna Indica*
8.	Year of commission	Year 2018
9.	Time period of construction	1 Year

Sl. No.	Parameters	Remarks from State Government
10.	Name of the scheme/funding agency	Department of Urban Development, Gov. of H.P.
11.	Design capacity	2.83 MLD
12.	Actual utilization	2.83 MLD
13.	Current population covered	15000 (Population Served)
14.	Design Year	15 Year Period
15.	Design population	25000 Souls
16.	Treatment efficiency (BOD, COD, TSS, TDS, N, P)	BOD ≤ 10ppm, COD ≤ 50ppm, TSS ≤ 20ppm, PH: 6.5-8.5, TKN ≤5 ppm, P ≤ 2ppm
17.	Components of STP (Name of the units)	Constructed Wetlands, Multi-Media Filter (MMF), Chlorine Contact Tank (CCT)
18.	Total Built-up area, in sq.m	1000 Squire Meter
19.	Capital cost	98 Lakh
20.	O&M cost/year	5 Lakh (Including Constructed Wetland Based STP)
21.	% of O&M charges collected through user charges/tax etc.	JSV Collected user charges collectively for whole city (50% of water bill cost)
22.	Labour requirement	2 Persons (Including STP and Sewerage Network)
23.	Details of user charges/taxes, Pl. specify	JSV Collected user charges collectively for whole city (50% of water bill cost)
24.	Advantages & disadvantages	
✓ As above		
25.	Recycle/reuse/disposal details of treated wastewater, if any	Currently no reuse available. Treated wastewater disposed in nearby surface running water body.
26.	Revenue generated through recycle/reuse, if any	Not Available
27.	Sludge generation, if any and its management	No sludge generated
28.	Sludge recycle/reuse/Disposal details, if any	No sludge generated

<table>
<tr><th>Sl. No.</th><th>Parameters</th><th>Remarks from State Government</th></tr>
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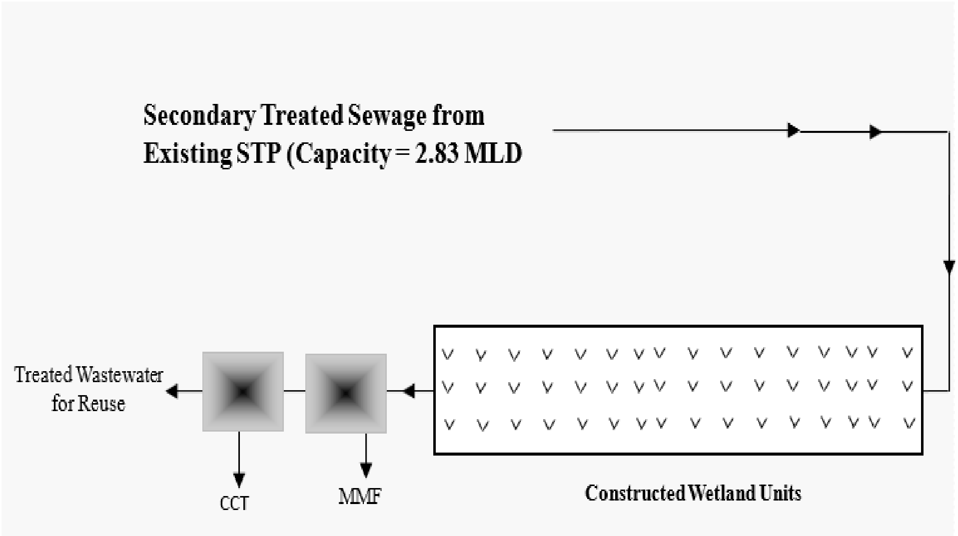
<tr><td colspan="3">
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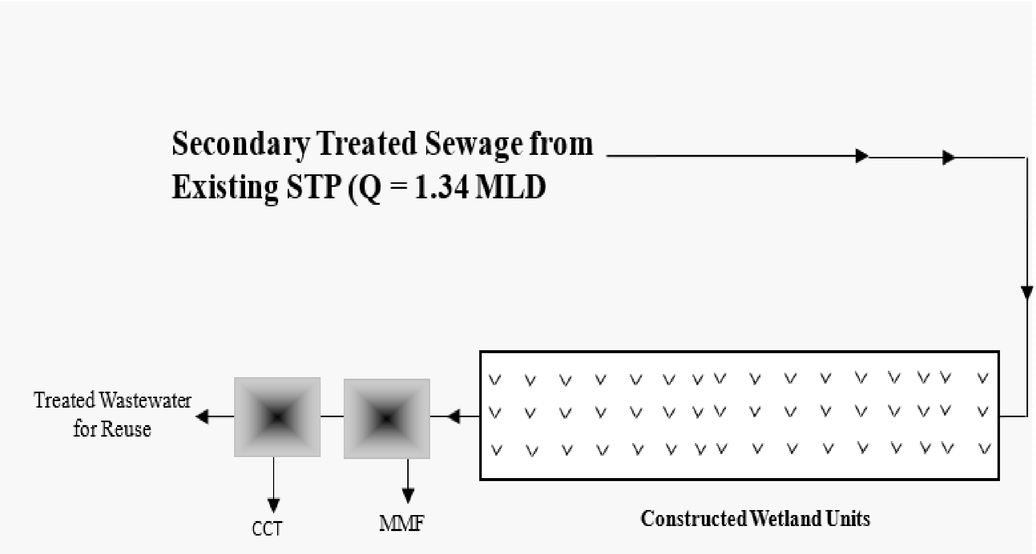
<tr><td colspan="3"></td></tr>
<tr><td>31.</td><td>Performance of the plant</td><td>STP constantly performing well since of its establishment.</td></tr>
<tr><td>32.</td><td>Any other remarks</td><td>Absolutely trouble-free operation and management.</td></tr>
</table>

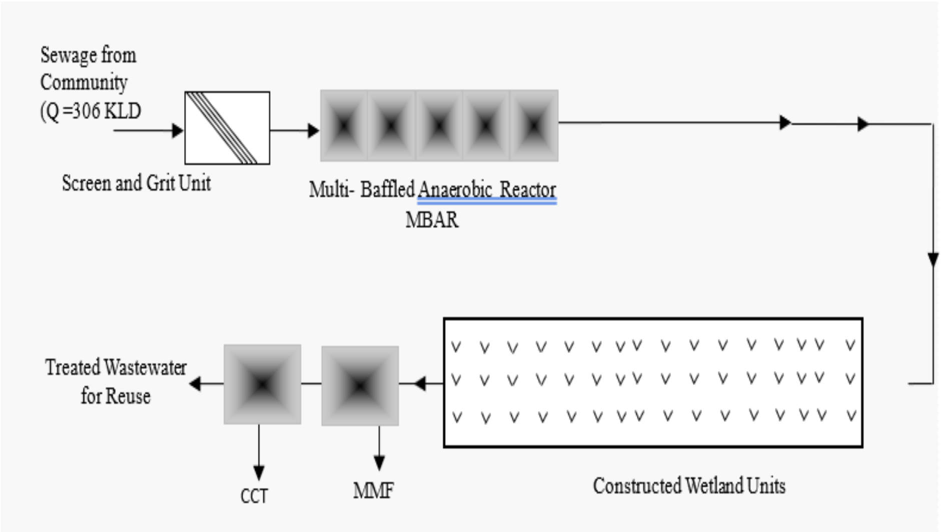
Sl. No.	Parameters	Remarks from State Government
F. 1.34 MLD Sewage Treatment Plant, Nagrota Bagwan, Distt. Kangra H.P.		
1.	Name of the city	Nagrota Bagwan
2.	Population as per Census 2011	12000 (Population Served)
3.	Current Population	10000 (Population Served)
4.	Current wastewater generation	1.20 MLD
5.	33. Characteristics of wastewater	BOD ≤ 30ppm, COD ≤ 100ppm, TSS ≤ 100ppm, PH: 6.5-8.5, TKN ≤15ppm, P≤5ppm
6.	Name of the STP /Technology	1.34 MLD STP Nagrota Bagwan, Distt. Kangra, H.P.
7.	Name of the plants used, if any	*Canna Indica*
8.	Year of commission	Year 2019
9.	Time period of construction	1 Year
10.	Name of the scheme/funding agency	Department of Urban Development, Gov. of H.P.
11.	Design capacity	1.34 MLD
12.	Actual utilization	1.34 MLD
13.	Current population covered	10000 (Population Served)
14.	Design Year	15 Year Period
15.	Design population	12500 Souls
16.	Treatment efficiency (BOD, COD, TSS, TDS, N, P)	BOD ≤ 10ppm, COD ≤ 50ppm, TSS ≤ 20ppm, PH: 6.5-8.5, TKN ≤5 ppm, P ≤ 2ppm
17.	Components of STP (Name of the units)	Constructed Wetlands, Multi-Media Filter (MMF), Chlorine Contact Tank (CCT)
18.	Total Built-up area, in sq.m	500 Squire Meter
19.	Capital cost	60 Lakh
20.	O&M cost/year	5 Lakh (Including Constructed Wetland Based STP)
21.	% of O&M charges collected through user charges/tax etc.	JSV Collected user charges collectively for whole city (50% of water bill cost)
22.	Labour requirement	2 Persons (Including STP and Sewerage Network)

Sl. No.	Parameters	Remarks from State Government
23.	Details of user charges/taxes, Pl. specify	JSV Collected user charges collectively for whole city (50% of water bill cost)
24.	Advantages & disadvantages	
✓ As above.		
25.	Recycle/reuse/disposal details of treated wastewater, if any	Currently no reuse available. Treated wastewater disposed in nearby surface running water body.
26.	Revenue generated through recycle/reuse, if any	Not Available
27.	Sludge generation, if any and its management	No sludge generated
28.	Sludge recycle/reuse/Disposal details, if any	No sludge generated
29.	STP sketch/layout drawing, if available	
		
30.	Photos	

Sl. No.	Parameters	Remarks from State Government
		
31.	Performance of the plant	STP constantly performing well since of its establishment.
32.	Any other remarks	Absolutely trouble-free operation and management.

Sl. No.	Parameters	Remarks from State Government
G. 306 KLD Sewage Treatment Plant, Dharamshala, Distt. Kangra H.P.		
1.	Name of the city	Dharampur
2.	Population as per Census 2011	2000 (Population Served)
3.	Current Population	2000 (Population Served)
4.	Current wastewater generation	220 KLD
5.	Characteristics of wastewater	BOD ≤ 350ppm, COD ≤ 700ppm, TSS ≤ 650ppm, PH: 6.5-8.5, TKN ≤30ppm, P≤10ppm
6.	Name of the STP /Technology	306 KLD STP Sandhol, Distt. Mandi, H.P.
7.	Name of the plants used, if any	*Canna Indica*
8.	Year of commission	Year 2020
9.	Time period of construction	1 Year
10.	Name of the scheme/funding agency	Department of Rural Development Gov. of H.P.
11.	Design capacity	306 KLD

Sl. No.	Parameters	Remarks from State Government
12.	Actual utilization	306 KLD
13.	Current population covered	3000 (Population Served)
14.	Design Year	15 Year Period
15.	Design population	3000 Souls
16.	Treatment efficiency (BOD, COD, TSS, TDS, N, P)	BOD ≤ 10ppm, COD ≤ 50ppm, TSS ≤ 20ppm, PH: 6.5-8.5, TKN ≤5 ppm, P ≤ 2ppm
17.	Components of STP (Name of the units)	Primary Treatment Unit, Multi-Baffled Anaerobic Reactor (MBAR), Constructed Wetlands, Multi-Media Filter (MMF), Chlorine Contact Tank (CCT)
18.	Total Built-up area, in sq.m	500 Squire Meter
19.	Capital cost	160 Lakh
20.	O&M cost/year	9 Lakh
21.	% of O&M charges collected through user charges/tax etc.	JSV Collected user charges collectively for whole city (50% of water bill cost)
22.	Labour requirement	2 Persons (Including STP and Sewerage Network)
23.	Details of user charges/taxes, Pl. specify	JSV Collected user charges collectively for whole city (50% of water bill cost)
24.	Advantages & disadvantages	
✓ As above		
25.	Recycle/reuse/disposal details of treated wastewater, if any	Currently no reuse available. Treated wastewater disposed in nearby surface running water body.
26.	Revenue generated through recycle/reuse, if any	Not Available
27.	Sludge generation, if any and its management	No sludge generated
28.	Sludge recycle/reuse/Disposal details, if any	No sludge generated
29.	STP sketch/layout drawing, if available	

Sl. No.	Parameters	Remarks from State Government
		
30.	Photos	
		
31.	Performance of the plant	STP constantly performing well since of its establishment.
32.	Any other remarks	Absolutely trouble-free operation and management.

Cost and Benefits of Constructed Wetlands

Prof. Indranil De
Professor
Institute of Rural Management Anand, Gujarat

Financing and managing the NTS projects is one of the biggest challenges, especially from the standpoint of replication and scaling. There are models whereby international organizations, central, state and local governments have funded NTS projects. The problem with such financing is that they often do not have a sound business plan from the applicants before the release of funds. Alternatively, there could be an incentive-based financing model supported by grants and subsidies, community-based loans, revolving funds and microcredits (Asolekar et. al, 2013). A microcredit is a small loan taken from own saving group (also known as a self-help group) or loans disbursed by venture capitalists known as microcredit organizations.

Cost-benefit analysis is a standard tool to analyze the economic viability of a project. However, as NTS projects involve the environment and society, mere accounting profitability may not make the projects sustainable. It is important to take into account the intangible costs and benefits of the project through social cost-benefit analysis (Molinos-Senante et. al, 2011). Social cost-benefit is a more holistic analysis encompassing financial cost-benefit analysis, economic cost- benefit analysis and distributional cost-benefit analysis (USAID, 2008). Balkema et. al, 2002 have detailed the list of indicators to be considered for sustainability analysis of wastewater treatment. However, to assess a social enterprise like an NTS, it is also important to un- derstand economic and distributional problems along with financial and environmental costs and benefits. Moller et. al, 2012 found that in Thailand the sustainability of CWs is determined by socio-cultural dimension; public perception, awareness and knowledge, local expertise and institutional clarity of roles.

Net present value (NPV) and benefit-cost ratio (BCR) are calculated for the social cost- benefit analysis of an environmental project (Babalola, 2020 and Verlicchi et. al, 2019). The costs include initial investment and incremental operating and maintenance costs. The benefits are measured through willingness to pay (WTP) surveys following the contingent valuation method (CVM). The CVM is a survey-based elicitation method to estimate the WTP of goods or services not traded in the market. A hypothetical market scenario is formulated and described to the survey respondents to elicit their WTP for the good or service. This process of eliciting WTP is called the stated preference method. Eggimann et. al, 2015 take into account settlement distribution and topography into the calculation of the cost efficiency of sewer systems. Kihila et. al, 2014 have suggested considering employment gains in cost- benefit analysis. Nevertheless, these approaches do not consider the cost of community participation explicitly. The cost of community participation may be accounted as the transaction cost of NTS. Transaction costs are comparative costs incurred by agents or stakeholders for planning, adapting and monitoring of the task under alternative governing structures (Williamson, 1981) and therefore the function of institutional designs (North, 1990). Transaction costs may also be defined as costs associated with defining, establishing and maintaining property rights (McCann, 2005).

In estimating transaction costs, financial and non-financial costs of collecting information, time spent and documentation for submission and service can be considered (Coggan et. al, 2015 and McCann et. al, 2016). Bostedt et. al, 2015 calculated transaction costs involved in the negotiations between two contestant parties. These calculations are essential in order to understand why community participation fails.

A few studies on NTS have examined the risk associated with the systems and social acceptability along with technical and financial feasibility (Starkl et. al, 2013a and Starkl et. al, 2013b). Although they took information regarding social acceptance or receptivity in the assessment, they did not calculate the transaction cost of acceptability or monitoring costs of potential health issues explicitly. There is a need for training and capacity building to increase wiliness to pay and community participation (Chakrabarti et. al, 2009 and Dhokhikah et. al, 2015). The costs for these activities need to be accounted for in a cost-benefit analysis.

The variables to be considered to assess the social cost-benefit of the NTS project have been depicted in Figure 2. It includes measures for both direct and indirect costs and benefits. It would be difficult to measure people's perceived risk, hesitancy and discomfort for NTA projects or reuse of treated water in terms of monetary or economic value. However, there are techniques through which the economic value of perceived risk, hesitancy and discomfort can be measured. These techniques are averting expenses or WTP calculated through the revealed preference method (as opposed to the stated preference method). Averting expenses are the expenditure made to avert the ill effect of bad odour or nuisances (Abrahams et. al, 2000). The additional expense people are willing to incur to use water other than that supplied through NTS is the WTP for getting rid of the hesitancy of using NTS treated water. The averting expenditure reveals the WTP for having an environment free from the perception of risks and discomfort and therefore being less hesitant to use treated water. Finally, the net present value (NPV) or benefit-cost ratio (BCR) of the social cost-benefit can be calculated.

It is also important to conduct a distributional analysis of NPV or net benefits of the project. Due to the political and economic factors, the net benefits would vary across economic classes. Some stakeholders may incur a negative NPV or net loss in the project while others may have positive NPV or net gain. To make those with negative NPV participate, stakeholders having positive NPV need to compensate stakeholders having negative NPV. If the compensation is possible then the business model would be sustainable. The Kaldor-Hicks Criteria of distribution would be satisfied if stakeholders with negative NPVs can be compensated by stakeholders with positive NPVs (Boardman et. al, 2017). In an ideal situation, no one should receive any negative NPV, which refers to the Pareto Criteria of distributional analysis. Distributional analysis of NPV amongst stakeholders should be considered after the overall NPV of the project is calculated as indicated in Figure 2.

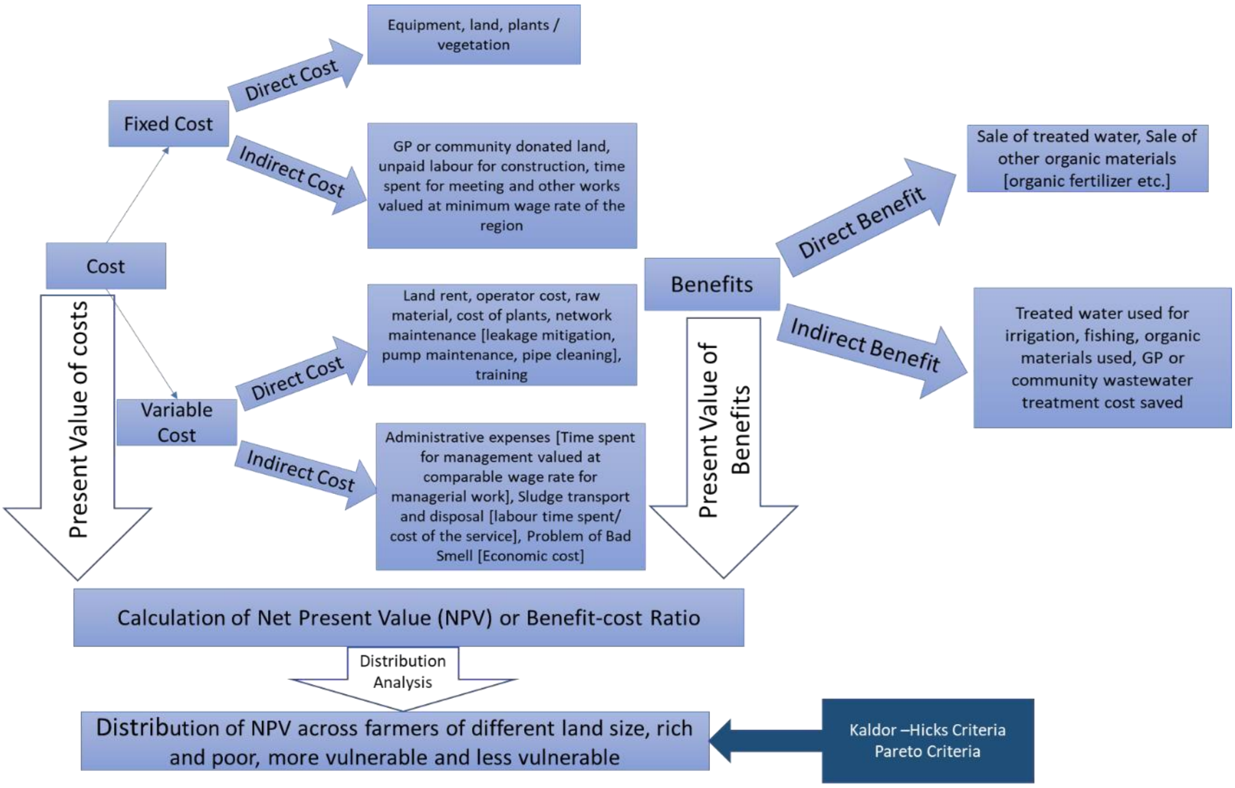


Figure 2. Calculation of social cost-benefit of NTS

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Regulations and Policies for Implementing Constructed Wetlands

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We first discuss the basis promises of environmental regulation, especially in the context of country. Environmental regulation should consider the following -standard-setting, monitoring, and enforcement, which are primarily the tasks of the PCBs and have secondarily become the realms of intervention by the judiciary (courts or NGT). Next, we discuss the role of institutional environment driven by regulations and policies for affect the development of Natural Treatment Systems (NTSs) in general and Constructed Wetland in particular. We discuss the difficulties of technology providers for sustaining and expanding green technology business.

Pillars of environmental regulation

Standard-setting

Water quality is regulated to ensure human and environmental health. Def ning acceptable water quality is enormously complicated because of two factors: the diversity of pollutants and the variety of uses to which the water is being put. A third complication is that when polluted water is discharged, it may not get used directly. Typically, it is released into a surface waterbody where it gets diluted by other "natural" flows before being used.

Water pollution standards in India (set under the Environment (Protection) Rules, 1986, Schedule VI, read with Section 3 (3–A) primarily focus on the quality of discharge, either into surface waterbodies or for direct use. The quality parameters or pollutants specified and their permitted limits vary depending on where the effluents are being discharged: inland waterbodies, coastal areas or direct use in (say) irrigation. Several assumptions appear to have gone into setting these standards; assumptions that may not hold today:

(i) The discharge standards for indirect use appear to assume that the receiving waterbodies (such as streams, rivers, ponds, and lakes) have inflows from pristine or rural watersheds, diluting the discharged pollutants' concentration. But this would not be true for seasonal rivers and may no longer be true even for perennial ones, as upstream catchments or stretches of the river get urbanized and industrialized.

(ii) The standards vary inexplicably: effluent discharge into any surface waterbody is regulated by 35 parameters, including heavy metals, whereas waste water for “land application” (that is, used directly in irrigation) is regulated by only 10 parameters with no parameters that cover heavy metals.

(iii) Certain sources are entirely unregulated. For example, limits for persistent organic pollutants (POPs) are specified only for industrial discharges, ignoring that farming is a significant source of POPs.

(iv) The standards are almost always concentration-based, not load-based, and therefore, the total amount of pollutants entering the receiving waterbody is not being regulated.

(v) Most significant gap is that no standards have been set for the ambient water quality of a surface waterbody, whether in general or corresponding to different uses that it might be put to.

(vi) the lax to non-existent water use standards, including irrigation water use, means neither state agencies supplying water for domestic use nor those building dams and irrigation canals can be held responsible when farmers, fisher folk, or villagers use river water downstream

(vii) The flowing water in channels, streams and rivers, including that which enters lakes and links upstream polluters to downstream users—both humans and aquatic species. Therefore, keeping in mind the catchment’s hydrology (what kinds of inflows are received from where), the regulator would have to set discharge standards, possibly load-based ones, for industries and other polluters in the catchment. Section 3 of the Water Act empowers the PCBs to do all this, and the CPCB has paid lip service to the idea of designated best use.

Monitoring

Adequately defined standards have to be matched by rigorous monitoring to identify situations where pollution levels are unacceptable, to trace them back to causes or sources on the one hand, and to estimate impacts on the other. Monitoring, therefore, needs to happen at multiple points: sources, in-stream/in aquifers, soil and food pathways, and the final recipient human populations and ecosystems. The monitoring effort in India is no doubt deployed at these multiple points. The primary focus, however, is on industrial sources. However, overall inspection levels are low. When it comes to domestic sewage, the monitoring is focused on the effluents from sewage treatment plants. Not only is this monitoring of STPs done poorly, but it ignores the fact that a significant fraction of domestic sewage in Indian cities never enters STPs. The PCBs have made no effort to track this fraction, let alone bring about any reductions. Similarly, there is no effort to monitor agricultural runoff for POPs.

Second, monitoring effort has no doubt increased when it comes to monitoring pollutants in transit: under the Global Environmental Monitoring System (GEMS) and the Monitoring of Indian National Aquatic Resources System (MINARS) schemes. But there seems to be a peculiar disconnect between monitoring and its use. As already mentioned, there are no ambient water quality standards, so the monitoring and tagging of the waterbodies into classes A–E or below E as per the WQC does not translate into any action as there is no legal requirement to abate pollution. Moreover, although many parameters seem to be monitored, the CPCB reports on river pollution classify river stretches into "priority classes" only based on BOD levels (CPCB 2011). Finally, the monitoring is often carried out at locations far downstream from the sources or only on major rivers where pollutants may get diluted or after the polluted water has already been reused.

Finally, in a diverse country like India with limited state capacity, citizen involvement in monitoring can make a big difference. The idea of citizen science is gaining popularity in other countries. In the Indian context, however, there is an enormous reluctance on the part of the regulatory agencies to engage with citizens. In the context of pollution measurements, too much is set store through tests by "authorised" agencies and little attempt is made to incorporate local knowledge.

The major problem of monitoring is not scarcity of funds. The problem lies with the shortage of human resources even when funding is available, poor or narrow training of staff and the lack of investment in monitoring equipment and technology upgradation

Enforcement

The powers given for enforcement include the ability to revoke or not renew consent, direct shutting down of operations, direct state utilities to shut off electricity and water supply to errant polluters, and finally, initiate criminal prosecution. Evidence that just the act of repeated inspection improves compliance. In the absence of powers to impose fines on its own, the PCBs will have to launch a criminal prosecution when there are repeated instances of violations. However, the record on criminal prosecution is abysmal.

Accountability

There is lack of accountability in standard-setting, monitoring and enforcement. The problem originates in the structure of the governing body (the “board”) of the PCBs: issues partly caused by the act and rules and substantially aggravated by practices followed by the state and central governments. Legally, the potential polluters are very well represented on the state boards. However, in general, there is no representation of the affected public (the potential pollutees). Nor is there any place for independent experts/scientists. Thus, the boards are hardly accountable to the public they are supposed to serve, nor are they really “autonomous” or “independent” of the state government as envisaged in the Water Act. Chairpersons often have poor qualifications, or may even come from industry, or are bureaucrats simultaneously holding other positions.

Adjuration

The NGT was specifically established at the behest of the Supreme Court to be a specialised forum to hear only environmental cases, with a panel consisting of judges and technical members who had experience in environmental sciences or regulation. Thus, the NGT was expected to provide an impetus to science-driven environmental adjudication in India and promote better access to justice. The tribunal has developed several substantive and procedural innovations that enable fact-finding, go beyond merely adjudicating the disputes presented before it and actively inquire into the situation and draw on science and scientific expertise in its decision-making—expansive powers that have been endorsed by the the Supreme Court (2021). These innovations enable the NGT to initiate proceedings suo motu, facilitate fact-finding on its own (which could otherwise be burdensome on the complainant) and tap into expertise available across multiple institutions evolve responses to violations.

Nevertheless, the NGT’s handling of water pollution cases leaves much to be desired. The problems range from conflict of interests in the NGT’s fact finding committees and non specification of quantum of penalty to becoming “super-regulator” by instructing prodding the regulators and functionaries to perform their duties. The latter is counterproductive as the appellate body may not be able to understand and function efficiently in matters of local environmental issues.

Institutional Environment

The need to develop a low-cost nature-based solution with high degree of reliability for wastewater treatment is felt by policy makers, practitioners, entrepreneurs, and also potential customers. Nevertheless, in spite of appreciation of the technology its adoption process faces several challenges from unsupportive institutional environment. The institutional environment driven by rules, regulations and processes plays a significant role for the adoption and progress of non-conventional wastewater treatment technology at a faster pace. A supportive institutional environment would allow potential entrepreneurs in conducting experimentation and searching customers.

Institutional Environment in Natural Treatment Systems

The institutional environment is not favorable to encouraging the adoption of green technologies. Dealing with local governments, whether they are urban municipalities or village Panchayats, can be challenging. The contractor whose systems are government funded face difficulties due to corruption in fund release. Few grants or discounted loans were available to the tech companies. There are relatively few technology providers in wastewater treatment as a result of the lack of assistance, particularly in the early stages of technology development. Nonetheless, partnering with academic institutions and other wastewater treatment professionals has shown to be quite beneficial for the technology providers. Government bodies like District Rural Development Agencies (DRDA) and international organization like UNICEF have aided development of training modules, imparting training, and IEC for stakeholders at the district and village levels.

The success of product-service systems (PSS) is largely dependent on the institutional arrangements in place. The Natural Treatment Systems (NTSs) developed by village Panchayats may not be maintained due to failures of or having no institutional arrangements for Operation and Maintenance (O&M). Sometimes the O&M of NTSs is handled by the building contractor for a duration of six months to a year. An official Annual Maintenance Contract (AMC) with the technology vendor for a predetermined duration is an alternative. There could be also no long term contract but technology provider can oversee or monitor projects for a charge. Extended formal maintenance agreements with system owners contribute to sustainability of the systems.

A constant feedback loop and problem resolution established during PSS can increase trust in NTS. This kind of feedback loops and accountability may be absent in conventional systems. The development of trust is extremely important to motivate the users or beneficiaries to contribute to the system's maintenance in the backdrop of people's free riding on good environment.

Summary

With rapid industrialization and urbanization, the problem of water pollution in India has escalated dramatically over the last few decades. The regulatory apparatus, has, however, lagged behind. Major gaps in standard setting, including lack of standards for ambient water quality, poor monitoring and weak enforcement by the pollution control boards are the major proximate causes. neither has the law in India regarding water pollution/quality standards kept up with the times, nor have the regulatory authorities, primarily the PCBs, come close to discharging their duties with the scientific and administrative rigour that would be required to address this problem. The structural weaknesses in the governance of the PCBs result in extremely poor accountability to the affected public, and the judiciary is not able to consistently and credibly strengthen this accountability Controlling water pollution will require a concerted effort to address these regulatory failures.

The constraints in terms of institutional arrangements are manyfold. First, there are no standard norms to comply with for treated greywater. At times local municipal governments impose certain norms and restrictions but there is a lack of uniformity. In urban areas value capture can be better if norms against discharge of greywater and other treatable effluents are strictly implemented. Second, the funding through the layers of public institutions and terms of association is fraught by corruption and slackness. The latter expands the sales cycle beyond the limits for any profitable venture for the entrepreneurs. Third, lack of institutional support for access to cheap finance, credible documentation of technology and accreditation. With institutional accreditation and certification, the initial trust deficit among potential customers may be reduced. Fourth, swings and uncertainty regarding political will for efficient operation may affect system's O&M severely, especially where public funds were used for construction. The process of programmes to spread the technology may get impaired due to frequent changes in bureaucracy.

Mainstreaming of CW for Wastewater Treatment Applications in India

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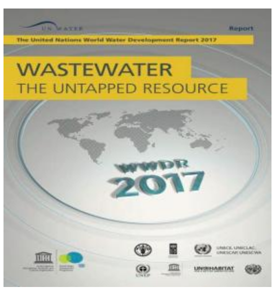
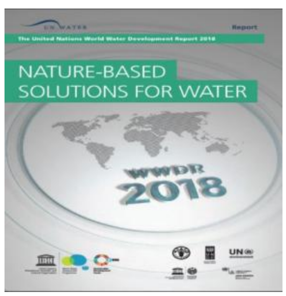
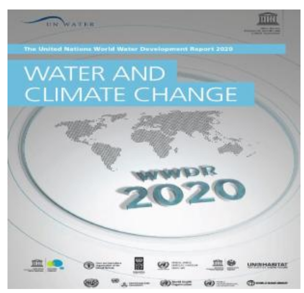
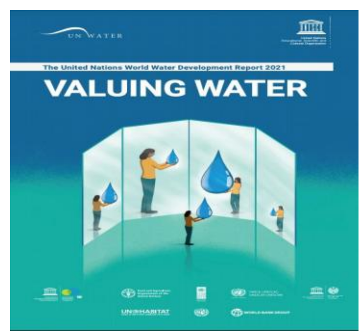
Freshwater and Wastewater

- Freshwater is limited, and water demand is growing
- Climate change and natural disasters further impose constraints on freshwater availability
- Wastewater treatment and reuse is the only solution
- UN WWDR focusing on wastewater as a resource
- SDG 6 can be achieved if we focus on WW as a resource









Dealing with Wastewater

- Only 37% of WW generated reaches STP/ETP. Majority of existing STP/ETP are overloaded- unable to treat effluent
- Existing installed capacity: 23K MLD; Gap of 39K MLD; investment required INR 2.5 lakh crore (USD 35 billion)
- Investment cost (capital+O&M) of STP: INR 80K to 100K/KLD (~40% is manpower, ~20% is electricity)
- Foot print area requirement: 1 to 0.48 m2/KLD
- NBS offer cost-effective and sustainable solutions

Nature Based Solutions (NBS)

- NBS are inspired and supported by nature and use, or mimic, natural processes to contribute to the improved management of water.
- An NBS can involve conserving or rehabilitating natural ecosystems and/or the enhancement or creation of natural processes in modified or artificial ecosystems.
- Upscaling NBS will be central to achieving the 2030 Agenda for Sustainable Development.
- NBS show particular promise in achieving progress towards sustainable food production, improved human settlements, access to water supply and sanitation services, and water-related disaster risk reduction. They can also help to respond to the impacts of climate change on water resources.
- Application of NBS for water also generates social, economic and environmental co-benefits, including improved human health and livelihoods, sustainable economic growth, ecosystem rehabilitation, and protection and enhancement of biodiversity.
- Despite large potential, NBS application is well below 1% of total investment in water resources management infrastructure.

Natural Treatment Systems (NTS)

- Constructed Wetlands (CW)
  - Horizontal sub-surface flow (HSSF)
  - Vertical sub-surface flow (VSSF)
  - Free water surface flow (FWSF)
- Duckweed Ponds (DP)
- Floating Wetlands (FW)
- Solar Aquatics System
- Waste Stabilization Ponds (WSP)

Applicability of NTS
Domestic wastewater
Agricultural wastewater
Industrial wastewater
Urban wastewater
Landfill leachate
Tannery wastewater
Winery wastewater
Pharmaceutical
Textile effluent
Dairy effluent
Storm water

NTS- CW

- NTS-CW is an artificially established compact wetland, where treatment is done with help of a substrate layer and aquatic plants (Canna indica, Typha latifolia, Phragmites australis)
- CW- can be used to treat WW (greywater or blackwater) from any source:
  - Domestic, Dairy, Tannery, Pharma/hospital, Agri- fertilizers/pesticides
  - Removes organic loads (nitrogen, phosphorous), metals, emerging contaminants (pharmaceuticals, drugs, disinfectants, pesticides)
- CW- can be used with streams, drains, lakes, ponds- protection of water source; in both urban and rural settings
- Cost-effective; easy to establish, operate and maintain; no or low energy costs
- Removal efficiencies of COD, BOD, TOC, TSS (80-95%); TN, TP (50-60%)

- Sizes: KLD to MLD
- Can be used in combination with other technologies to meet WW reuse standards (CPCB)

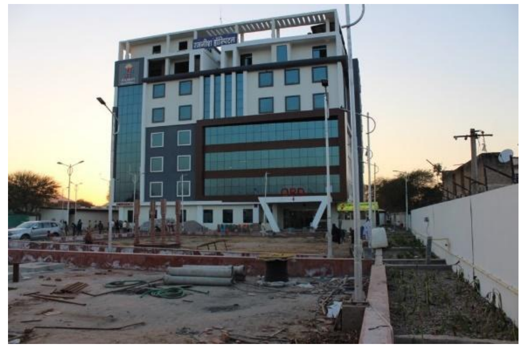
S. N.	Type of Wastewater	Type of constructed wetland	Country	References
1	Domestic wastewater	HSSF	Rajyapal Bhavan, Mumbai, India	Phytorid, CSIR-NEERI
		HSSF	Lonar lake, India	Phytorid, CSIR-NEERI
		HSSF	Teen Murthi Bhavan, New Delhi, India	Phytorid, CSIR-NEERI
		HSSF	Nashik, India	Warne and Wagh, 2014
		HSSF	Agra, India	Kumar and Asolekar, 2016
		HSSF	Chennai, India	Bhaskar et. al., 2009
		HSSF	Patancheru, India	ICRISAT
		HSSF	Ludhiana, India	Kumar et. al., 2015
		VSSF	New Delhi, India	Kaur et al., 2012
		HSSF, VSSF	MP, India	Prashant et al., 2013
		HSSF,VSSF	Egypt	Abou-Elela et al., 2013
		HSSF,VSSF	Germany	Nivala et al., 2013
		HSSF	Brazil	Avelar et al., 2014
		VSSF	China	Guo et al., 2014
		FWSF	Greece	Galanopoulos et al., 2013
2	Agricultural wastewater	HSSF, HSFW	China	Sun et al., 2013
		HSSF	China	Xu et al., 2014
3	Industrial wastewater	HSSF	Pakistan	Zebet al., 2013
4	Urban wastewater	HSSF	Italy	Leto et al., 2013
		VSSF	Spain	Martín et al., 2013
5	Synthetic wastewater	HSSF	Sri Lanka	Weerakoon et al., 2013
		HSSF	Spain	Valles-Aragon et al., 2013
6	Fresh oil-field produced wastewater	FWSF	United States	Alley et al., 2013
7	Marine aquaculture wastewater	HSSF	United Kingdom	Webb et al., 2013
8	Landfill leachate	HSSF	Colombia	Madera-Parra et al., 2015
9	Tannery wastewater	HSSF	Portugal	Calheiros et al., 2014
10	Winery wastewater	HSSF	South Africa	Sheridan et al., 2014
11	Pharmaceutical wastewater	HSSF, VSSF, HSFW	Canada, China, Denmark, Italy, Portugal, USA Singapore, Spain etc.	Li et al., 2014
12	Storm water	HSSF, FWSF	Korea	Choi et al., 2014
		VSSF	Korea	Niu et al., 2014
		FWSF	Canada	Han et al., 2014
13	Swine Wastewater	HSSF	China	Liu et al., 2014
14	Boron mine wastewater	HSSF	Turkey	Turker et al., 2014
15	Textile effluent	VSSF	Pakistan	Shehzadi et al., 2014
16	Highway runoff	HSSF	China	Fu et al., 2014
17	Dairy effluent	HSSF	USA	Tunçsiper et. al., 2015
		HSSF	Kerla, India	Dipu et.al., 2010

Housing

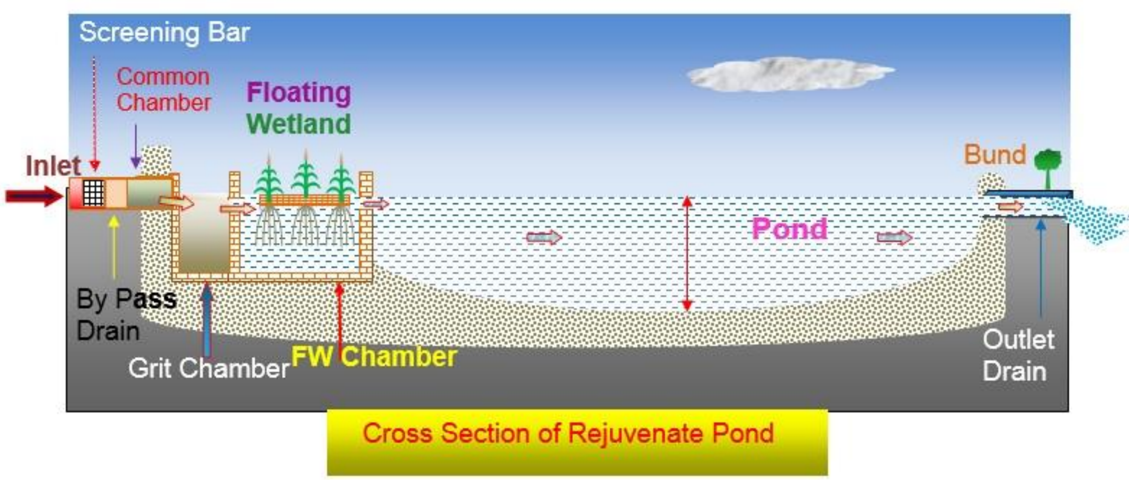
Constructed Wetland for treatment of domestic wastewater from residential area (NIH Colony Roorkee)

Constructed Wetland for treatment of domestic wastewater from residential area (NIH Colony Roorkee)

Hospital/HCF



With a Pond



Rejuvenation of a Pond in Ibrahimpur Village (Dist. Haridwar, Uttarakhand)

Impact of Rejuvenation of Pond

Parameters	Before Rejuvenation	After Rejuvenation (Jan 2018)
pH	7.37	7.71
Turbidity (NTU)	48	43.1
Alkalinity (mg/l)	578	276
NO_3 (mg/l)	10.2	0.98
PO_4 (mg/l)	8.46	0
DO (mg/l)	0.25	5.5
FC (MPN/100 ml)	240	150

GW level enhanced and GW quality improved in nearby handpumps



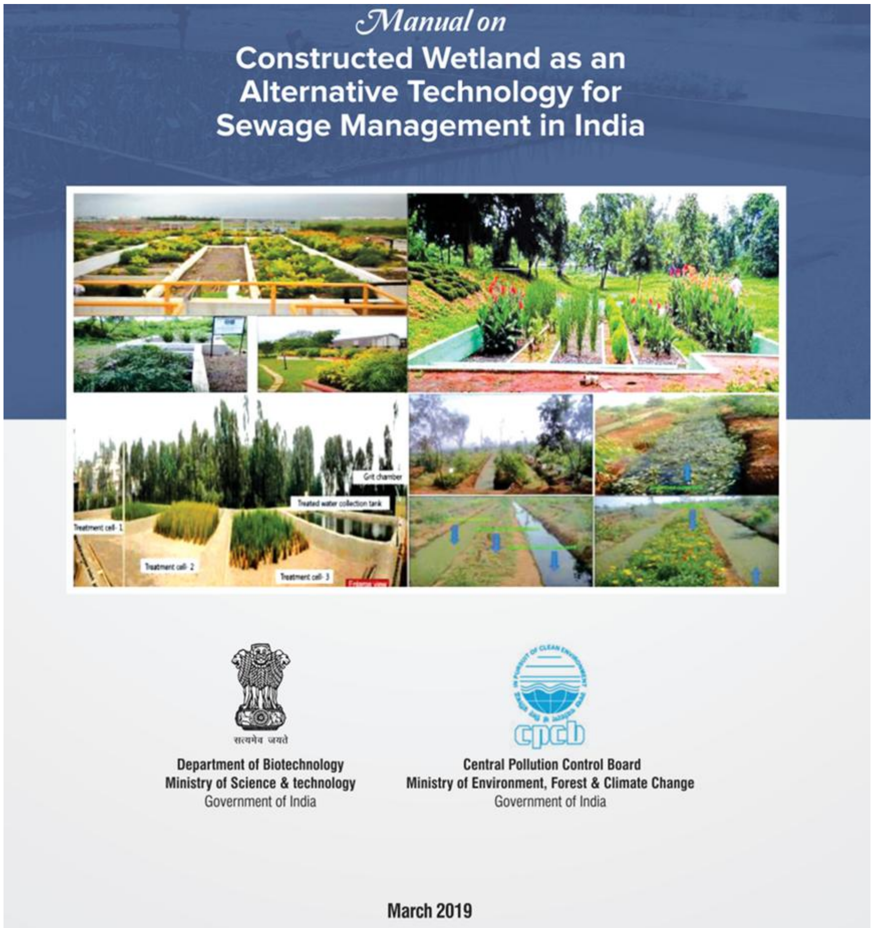


Why CW not thriving in India?

- Thousands of installations available in India, but lack visibility and recognition
- Data monitoring is lacking
- Seen as a competitor by conventional STP industry
- Good inventory is required for ready reference
- Extensive field-scale CW are needed
- Capital costs are high (esp. land)
- Considering O&M costs for ~30 years, CW offer economic solution
- Publications on CW started growing since mid-nineties (1995)
- Policy for reuse of treated wastewater (Gujarat, Jharkhand, Karnataka, Maharashtra, Haryana, Punjab, UP, WB)

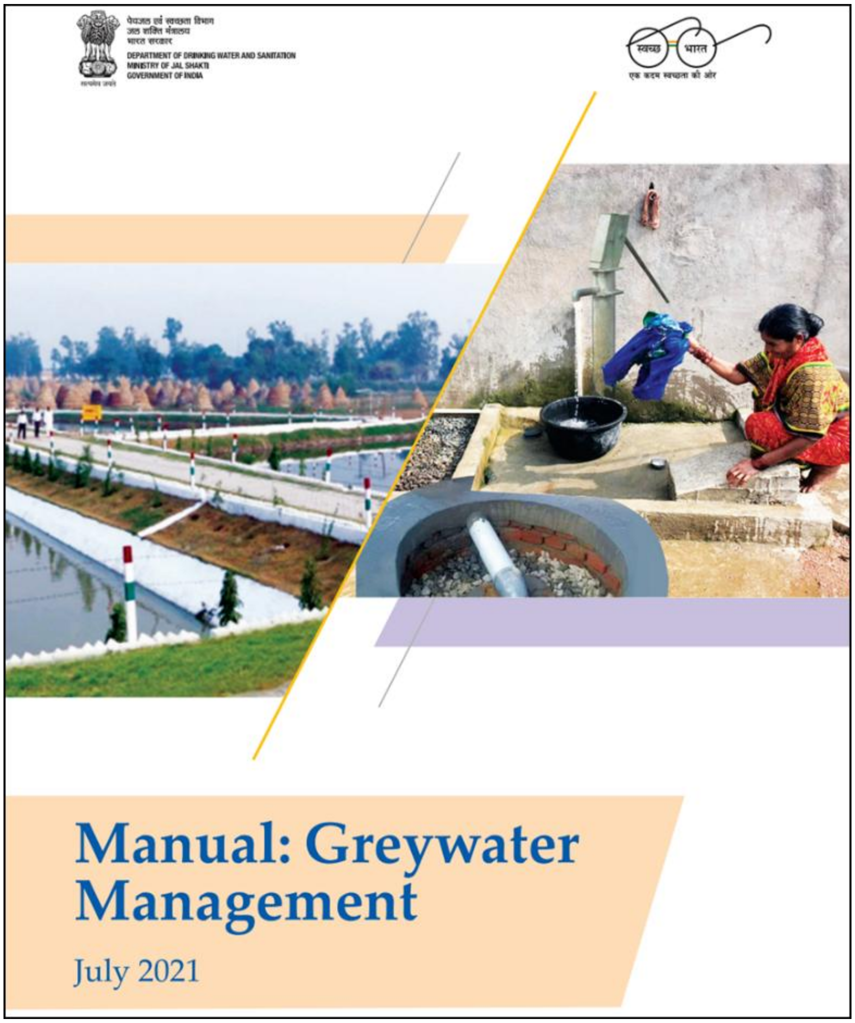
What can and should be done- at R&D level

- Sensitization of policy makers and decision makers at State & district level
- In urban settings (with land constraints), hybrid treatment systems (Mech+CW) may be used
- Combined with RWH systems, CW offer sustainable WM solution in industries, HCF, housing societies
- Availability of TP with business model for different applications [of different sizes & configurations (depending on load & type of WW) according to requirement]



What can and should be done at Govt/policy level

- Potential of employment generation (e.g. thru MNREGA)
- Availability of skilled manpower to establish CW- explore "Skill Council for Green Jobs"
- Aggressive marketing required
- Financial incentives required from government, banks (e.g. green projects/schemes for sustainable development)
- Link w/flagship govt schemes-Swachh Bharat Mission, JJM, NMCG, Smart City, Sujlam 2.0
- Projects under CSR/philanthropic funding
- Need to be promoted through manuals/ standards of CPHEEO, CPCB, CPWD, Indian Green Building Council Certification
- Establish a focused group on Constructed Wetland for WW Management



Green Infrastructure and Grey Infrastructure

- Green Infra- rainwater harvesting structures, green roofs, rooftop gardens, ponds, wetlands, permeable pavements
- Grey Infra- wastewater treatment plants, drains, water pipelines- always in demand due to growing population
- Green infra may complement grey infra demand- green infra can reduce pressure on grey infra by naturally filtering out non- point source pollutants
- A synergy is required between green and grey infrastructure development

Summary- Takeaways

- SDG 6 can be achieved if we focus on WW as a resource, and focus on NBS as appropriate solutions
- CW provide ‘green’, decentralized, cost-effective and sustainable solution for water and wastewater management

- CW are easy to establish, operate and maintain; no or low energy costs; can be used in variety of applications
- Co-benefits- energy savings, reduced GHG emission, GW recharge, nutrients recovery, harvested biomass
- CW need to be propagated widely in India- will need skilled manpower to design, install and O&M
- Seen as a competitor by conventional STP industry
- Can be used in combination with other technologies to meet WW reuse standards (CPCB)- synergy required
- Economic/financial incentives are required from govt.